Department of Mechanical and Aerospace Engineering

The Dynamic Modelling of Biomass Boiler Systems: A Training Tool

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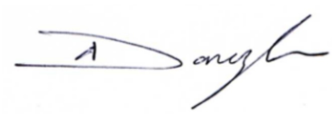
Signed:  Date: 01/09/2012

PROJECT ABSTRACT

Biomass boiler systems are being installed increasingly across the world. However, the exact operational performance of these systems is not widely understood. Often biomass boilers are installed alongside thermal stores or buffer vessels that are inappropriately sized for a particular heating load. This often results in a small percentage of the heating demand being provided using the biomass boiler systems. Consequently, auxiliary fossil fuelled boilers are commonly used to make up for the proportion of the heating demand that these systems are incapable of providing. Similarly, biomass boilers are often over-sized as a large percentage of the peak heating demand. This can result in increased costs and can impact low load system operation. In fact, recent research (1) in the UK has found that oversized biomass boilers with inadequately sized thermal stores with limited control systems contributes significantly to low system efficiency in many installations across the country.

The motivation of this project is to increase the understanding of several key biomass boiler systems by developing a training tool in an Excel spreadsheet to accurately model the operation of several different piping configurations and allow the dynamic performance to be examined in detail. This has been achieved by developing a collection of simultaneous equations that describe the operation of each biomass boiler system under different demand scenarios before encoding these equations into the training tool. The training tool calculates the mass flow rates and temperatures throughout various biomass systems for each five-minute time step of an entire design winter day. This includes the heat-up and cool down profiles associated with biomass boilers amongst other parameters.

The training tool also provides a faster than real time simulation for each of the different configurations that can be run within the training tool to illustrate the performance of the specific systems to the user in providing hot water to the load reliably and whenever there is a demand. This allows the performance of a particular biomass boiler system to be examined quickly and permits important design decisions to be made in the planning phase prior to installation.

Finally, the training tool is demonstrated in this report using two case studies for two differing demand profiles, each created using the Biomass Boiler Sizing Tool developed by the Carbon Trust. Each demand profile is explained in detail and the results from the training tool examined to highlight the strengths and weaknesses of the tool and to help choose a suitable biomass boiler configuration for each demand profile.

The results from the tool have shown how correctly sized components can significantly increase the performance of a biomass boiler system, while poor design decisions can vastly impact the capability of these systems.

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Firstly, I would like to thank David Palmer of *The Campbell Palmer Partnership Ltd* for his assistance and advice throughout this project. If he had not suggested this area of study and inspired me to take it up it is unlikely that I would have pursued this project that I have enjoyed so much.

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NOMENCLATURE

T_{bf}	Boiler Flow Temperature (°C)
T_{br}	Boiler Return Temperature (°C)
T_{bmr}	Boiler Minimum Return Temperature (°C)
ΔT_b	Boiler Temperature Drop (°C)
T_{ls}	Load Supply Temperature (°C)
T_{lr}	Load Return Temperature (°C)
T_{lrs}	Load Return Supply Temperature (°C)
ΔT_l	Load Temperature Drop (°C)
T_{TS}	Temperature of Flow From Thermal Store (°C)
T_t	Temperature at time t (°C)
T_o	Temperature at time zero (°C)
$\dot{m}_b$	Boiler Mass Flow Rate (kg/s)
$\dot{m}_{bl}$	Back-End Loop Mass Flow Rate (kg/s)
$\dot{m}_l$	Load Mass Flow Rate (kg/s)
$\dot{m}_{lrs}$	Load Return Supply Mass Flow Rate (kg/s)
$\dot{m}_{bs}$	Boiler Supply Mass Flow Rate (kg/s)
C_p	Specific Heat Capacity (J/kg°C)
L	Demand from Load (kW)
R	Boiler Rating (kW)
TDR	Boiler Turndown Ratio
VR	Boiler Volume Ratio
V	Volume (litres)
TS_{charge}	Thermal Store Charge (litres)

1. Introduction

A large proportion of the UK's energy demand is for hot water. Traditionally gas and oil fired boilers have been used to meet this demand, however biomass boilers have become more popular in recent years with the increasing pressure to reduce carbon emissions. Importantly, these boilers must be designed to provide heating reliably and whenever there is a demand. Unfortunately biomass boilers are relatively expensive compared to more traditional options and are not as dispatchable. A major disadvantage of biomass boilers is the time it can take for the water to be heated to the required flow temperature and the need for the boilers to be cooled upon shutdown. Additionally, frequently turning biomass boiler on and off is very inefficient, wasting a considerable amount of fuel over the period of a year and cause unnecessary wear and tear on the components of a boiler system.

It is possible to avoid scenarios such as this by combining biomass boilers with large thermal storage and buffer vessels. Depending on the manufacturers recommendations many biomass boilers require a method of dumping the surplus heat stored within the boiler upon shut down. This prevents the components within a boiler from overheating and becoming damaged and the water inside the boiler from evaporating. A **buffer vessel** allows the additional heat stored within a boiler to be extracted and then utilised while the boiler is heating up the following day. Similarly, **thermal stores** can be used to increase the efficiency of a biomass boiler system and reduce the boiler rating as a percentage of the peak heating demand from a load (2). This is because it provides a method of storing hot water over night when demand is low while allowing the surplus heat to be extracted from the boiler upon shut down. This store of hot water can then be utilised when a demand is reintroduced the following morning together with the biomass boiler to match the peak demand for hot water and reduce the use of any auxiliary boilers. However, it is important to mention that the suitability of methods such as this is highly dependent on the characteristics of the particular load. A large thermal store may not be suitable in scenarios when the demand from the load remains constant throughout the entire day since there is little opportunity to store surplus hot water.

Unfortunately, in practice these methods to increase the efficiency of biomass boiler systems are often misunderstood and systems are often sized incorrectly. This frequently results in biomass boilers systems which are incapable of providing the desired amount of hot water to the load when required, with more dispatchable fossil fuelled auxiliary boilers being used to provide the heating demand that can not be supplied. This can be costly, inefficient, and increase the carbon emissions attached to the process of supplying hot water to a heating load. To combat these issues it is important that manufacturers and providers of biomass boiler systems have an in depth understanding of the operational performance of each of the typical biomass system configurations that are available so that the systems can be sized appropriately for each specific heating load.

The purpose of this project is to develop a model of biomass system operation, which allows the dynamic performance to be examined. This includes buffer vessels, thermal stores, and auxiliary boilers. The purpose of the tool is to assist a user in understanding the performance of different system component and hydraulic configurations. There are many types of biomass boiler systems and the design can differ greatly from one configuration to the next. Consequently, it is important that the operation of each configuration is considered carefully and a set of linked simultaneous equations is created to describe the typical biomass circuit configurations that are encountered. These equations have been encoded into an Excel spreadsheet and connected to several demand profiles to predict the performance of a particular configuration in providing hot water to the heating load over the course of a 24-hour period.

Additionally, the training tool allows the outputs from the Biomass Boiler Sizing Tool, developed by the Carbon Trust, to be used as inputs. In other words, a user can create a demand profile for a given building, before sizing the biomass boiler and any additional equipment such as buffer vessels and thermal storage, prior to using these specifications as inputs to the training tool. The Carbon Trust tool sorts the issue of sizing boiler components correctly, while the training tool developed for this report makes sure that the intended performance is delivered by ensuring that the desired configuration is appropriate.

The tool can then be used to indicate the performance of these specifications in partnership with the demand profile created for a design winter day. However, this is not only limited to a design winter day as the demand profile for any period throughout the year could be used and the boiler system operation examined over the course of that particular day. This allows the specifications to be examined during a design summer day as well as a design winter day. The hope is that the training tool could one day be used as an add-on to the current Biomass Boiler Sizing Tool to help designers choose the appropriate and optimal biomass boiler piping configuration for a particular demand profile.

Furthermore, an important part of the project has been creating a reasonable representation of the heat-up and cool-down periods associated with all biomass boilers. When a demand is introduced to a biomass boiler system it takes a length of time for the water to be heated up to the desired flow temperature and the boiler lining to warm to temperature before the demand from the load can be satisfied. Similarly, it is necessary that realistic cool-down profiles are included into the training tool. When the demand from a biomass boiler system is removed it is important that the boiler is cooled upon shut down to prevent the internal components from over heating and becoming damaged. For this reason, the training tool also considers the cool-down periods typical of biomass boilers.

Finally, the results provided by the tool for each biomass boiler system configuration are illustrated on a dynamic graphical output which has the ability to display the key information in a faster than real time simulation. In other words, a five-minute time step would be simulated in approximately one second within the training tool. This allows the user of the training tool to quickly visualise the operation and performance of the desired configuration throughout the course of a design winter day, before making key design decisions prior to deciding upon the final biomass boiler system for a specific heating load. The training tool allows the user to run a simulation for the desired configuration and demand profile, which displays the flow rates and temperatures throughout the piping network, including the charge of any thermal stores or buffer vessels during each five-minute time step of an entire day.

This report will begin by explaining the theory behind each of the key components related to a biomass boiler system before detailing the simultaneous equations that govern the operation of each of the key biomass boiler piping configurations considered in this report. Additionally, the training tool will be explained in detail to aid a potential user. Finally, a case study of two demand profiles used alongside the training tool will demonstrate the operation of the tool and highlight its strengths and weaknesses. The flow chart below illustrates how the training tool is used.

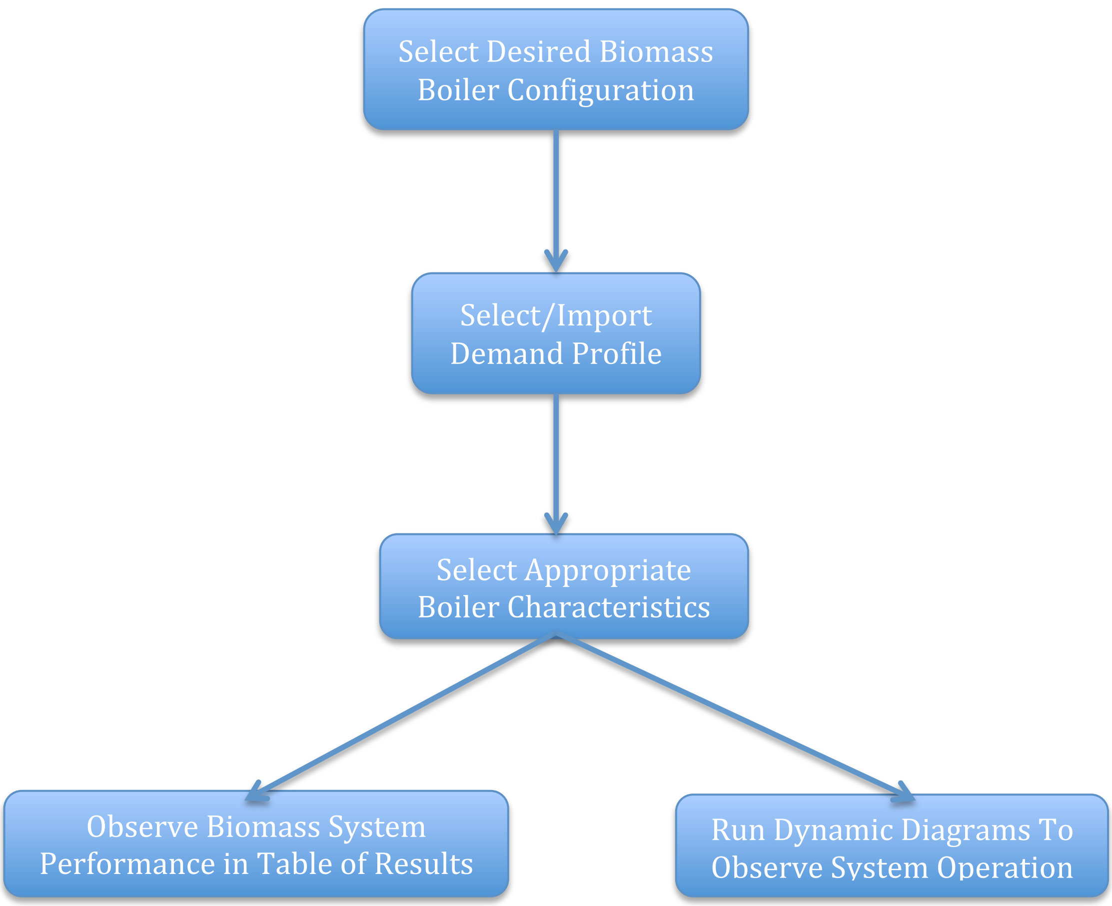


Figure 1.1: Flow Chart of Training Tool Operation

2. Biomass Boiler Systems

Three main configurations have been examined for inclusion in the training tool. All of the configurations include a biomass boiler with the addition of the following components:

- Back-end valve and a three-port mixing valve.
- Back-end valve, buffer vessel, and a three-port mixing valve.
- Back-end valve, four-port thermal store, and a three-port mixing valve.

Furthermore, the training tool includes each of the configurations listed above with the addition of an auxiliary boiler. The majority of biomass boiler systems include some form of auxiliary fossil fuelled boilers to help meet the peak-heating load. Consequently, including the operation of an auxiliary boiler into each configuration is seen as important to improve the usefulness of the training tool. An auxiliary boiler has been attached into each configuration in two distinct approaches. This will be explained further later in the report.

The biomass boiler systems become increasingly complex and more difficult to model with each additional component that is added. It is important that each system is considered separately to ensure that the operation of each system is modelled accurately. For this reason the configurations listed above are in order of increasing complexity. Each of the components listed in the configurations above are explained in detail within the following sections of the report. A strong understanding of key components is essential for the successful modelling of each system.

2.1 Biomass Boiler Overview

2.1.1. Boiler Types

There are several biomass boiler types, each of which operates in a slightly different manner. This section of the report will give a brief overview of the key biomass boiler types and the significance of each to the training tool that has been developed.

Each biomass boiler will have a **turndown ratio**. This refers to the minimum output that the boiler can produce (3). For example, a 100kW boiler with a turn down ratio of 4:1 will have a minimum output of 25kW. Additionally, the boiler type will influence the required size of any buffer vessel. This is discussed further in the buffer vessel section of the report. Each of the biomass boilers described in the sections below are included into the training tool as variables. This includes the boiler characteristics such as the fuel feeding mechanism, fuel type, and refractory lining thickness. For this reason, it is important that the characteristics of each boiler type are taken into consideration by the training tool to allow reasonable heat-up and cool down profiles to be made and allow buffer vessels to be sized appropriately.

Stoker Burner

Typically, stoker burners are the smallest and simplest of the biomass boiler types. The grate, which supplies the combustion chamber with fuel is usually small and runs within a cast iron tube. The fuel moves along the length of the boiler until the burnt ash falls from the open end of the grate. This is illustrated in figure 2.1.1 below, which shows a typical stoker burner biomass boiler.

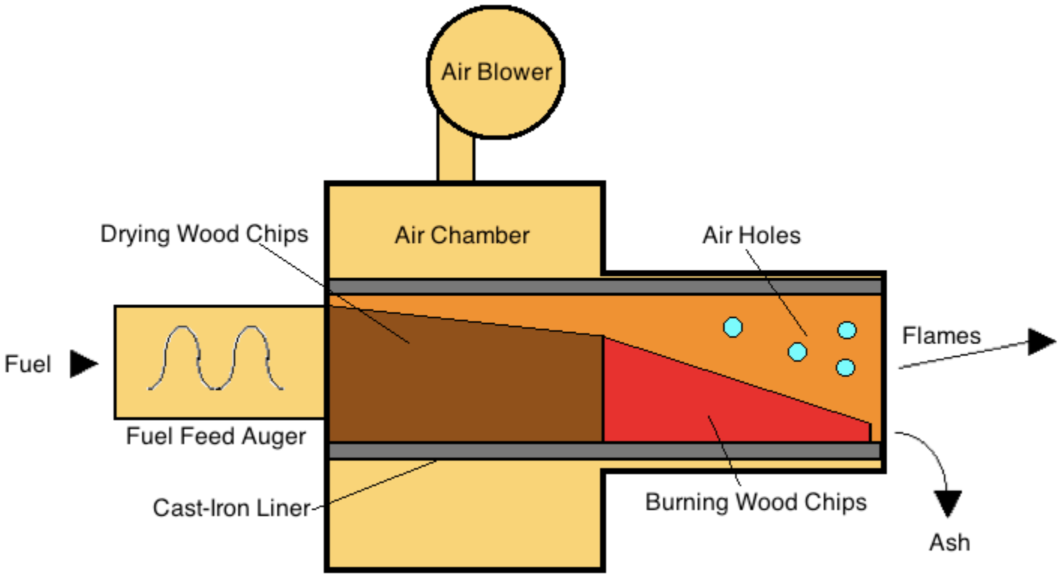


Figure 2.1.1: Diagram of a Stoker Burner

Unlike the two other main categories of biomass boilers, a solitary fan is used to provide stoker burners with the primary and secondary air feed. This can create difficulties when controlling the temperature on the grate and further along in the combustion chamber. It is important that the temperature of the grate is low enough to avoid slag formation while ensuring that the temperature inside the combustion chamber is high enough to achieve complete combustion of the fuel mixture and the associated wood emissions. To avoid the temperature on the grate being too high and slag forming over the grate the return water to the boiler is used to cool the grate (4).

When the demand is removed from a stoker burner they are design to operate in slumber mode to avoid the boiler from shutting down completely. This requires a small amount of fuel to maintain a minimum of approximately 2-3% of the boiler maximum output at all times. Additionally, stoker burners are capable of responding to load variations quickly and can benefit from a turndown ratio of 4:1 and even higher (4).

However, stoker burners also have some significant limitations that restrict there use. The woodchips used must be consistent and small in size, with a maximum moisture content of approximately 30%. If the fuel is any wetter then black smoke can be produced. For this reason, small variations in fuel mixture can have a significant impact on the boilers performance. Furthermore, incomplete separation of primary and secondary air can result in slag formation above the grate and incomplete combustion of the fuel. The grate within the boiler also requires to be cooled using water from the boiler upon shutdown and the feed auger emptied to prevent burn-back. Alternatively, flap valves can be used between the auger and the grate to remove the need to empty the auger upon boiler shutdown (4).

Underfed Stoker

Unlike stoker burners, underfed stoker burners can accept wood pellets and woodchips with moisture content of up to 30% and are available in a wide range of boiler sizes. The boilers are able to avoid issues with incomplete separation of primary and secondary airflow by employing separate primary and secondary combustion air control. The fuel is inserted into the combustion chamber through an auger feed, which moves the fuel up from underneath forming a dome of fuel within the combustion chamber. The biomass burns from the top of the dome downwards reducing the risk of burn-back along the auger when the boiler is turned off (5). A typical underfed stoker boiler is shown in figure 2.1.2.

The primary airflow is introduced from beneath the combustion chamber and rises around the dome of fuel. The ash from the burnt fuel falls from around the dome into an ash pan. Secondary air is introduced above the combustion chamber to burn off any gas emissions from the burning fuel below (5).

The turndown ratio of underfed stoker boilers can be as low of 2:1 and slag formation can cause the boiler to flame-out. Finally, these types of boilers have been known to react slowly to changes in demand due to the long heat-up and cool-down periods associated with the thick firebrick lining (5).

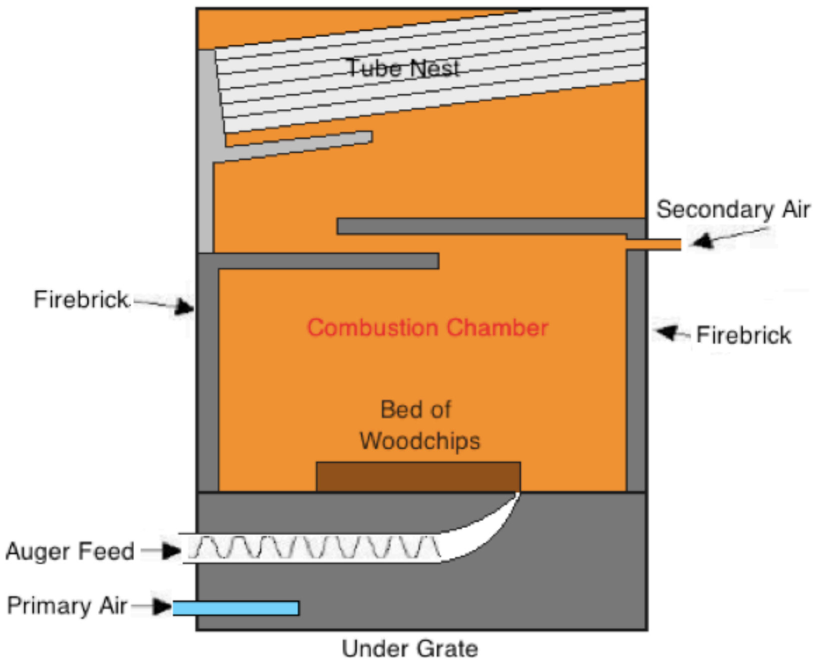


Figure 2.1.2: Diagram of an Underfed Stoker

Moving Grate

There is a large variety of moving grate boilers but typically they are designed to have a larger capacity than the alternatives. They include a large size range from small 10kW boilers to huge industrial 10MW boilers. The boilers include a sloped moving grate, which supplies the fuel to the biomass boiler, through the combustion chamber and onwards to an ash pit. This allows the boilers to be more fuel flexible than others since the bed of fuel is mixed mechanically allowing fuel of different particle size to be used. The fuel variety includes wood chips, and wood chip and peat mixtures amongst others (6). Figure 2.1.3 below shows a typical moving grate boiler.

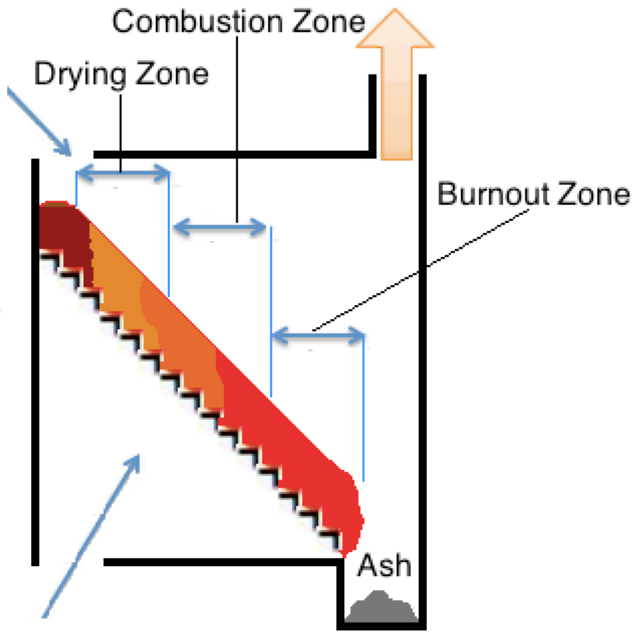


Figure 2.1.3: Diagram of a Moving Grate Biomass Boiler

The grate is made partially from chromium (up to 40%) to provide corrosion resistance and is angled within the boiler. The angle is dependent on the fuel type and moisture content, with wetter fuel mixtures resulting in a stepper grate angle. When dryer fuel types are used the grate can be angled horizontally. This design allows fuel to be used with moisture contents of up to 55% allowing a large variety of biomass fuel types to be utilised. The moisture content of wetter fuels is reduced using a reverse flame design. Moving grate boilers are designed in such a way that wetter fuel types can be dried out when moved through the first stages of the boiler. By the time the fuel has reached the combustion chamber a proportion of the moisture has been evaporated and the fuel will burn more evenly and completely (6).

Air is introduced to the boiler from underneath the grate and rises evenly between the bars of the grate. The secondary air is pumped above the firebed allowing the emission from the fuel to be burnt off. Air fans are also employed occasionally to assist the secondary airflow when burning off the wood gases above the firebed. Importantly, the primary and secondary airflows can be varied during combustion allowing the combustion process to be improved (6).

Typically, two different fuel-feeding mechanisms are used to provide a moving grate boiler with biomass fuel. On smaller boilers an auger is typically used, however ram stokers are used more often with larger boilers to help push the fuel into the combustion chamber of the boiler.

However, moving grate boilers react slowly to changes in demand and take a considerable length of time to heat-up and cool down due to the thick thermal linings. Additionally, moving grate boilers often operate in slumber mode with a heat output of 30% when burning wet fuel. Furthermore, heat exchangers are occasionally required within larger moving grate boilers to remove the heat within the boiler upon power failure (6). Overall, moving grate boilers provide the best design for wood boilers but are complex and expensive compared to the alternatives.

2.1.2. Biomass Fuel and Legislation

Some see biomass boilers as 'carbon neutral' energy systems since the fuel used is easily replenished and an equivalent volume of CO_2 has been taken out of the atmosphere during its growth prior to releasing the CO_2 as emission during the combustion stage. For this reason biomass boilers are considered more environmentally friendly than their fossil fuelled counterparts and many grants and incentives have been made available to potential investors to support the growth of the industry. A wide variety of grants and support is available through the *Biomass Energy Centre (7)*. The grants and schemes that are available are split to support three main categories:

1) Purchase, installation, and development of equipment.
2) Support for fuel chain supply
3) Consultancy and advice

Further information on the grants and support available can be found on the *Biomass Energy Centre* website (7).

Biomass Fuel

There are several biomass fuel types that can be used as fuel within biomass boilers. It is important that the type of fuel used is carefully considered due to the differences in the properties of each. In fact, the design of biomass boilers can be highly dependent on the characteristics of the fuel that is used, while the efficiency of a boiler is closely related to the type of fuel that is used.

A wide variety of biomass can be used as fuel within biomass boilers, however the majority of boilers operate using woodchips or wood pellets. Small systems such as batch fed boilers are capable of running on a wide variety of fuel including logs, waste wood, offcuts, and straw (8).

It is important to note that the quantity of fuel required depends on the moisture content of the fuel. The higher the moisture content, the more fuel will be required which can effect storage considerations (8).

2.1.3. Biomass Boiler Operation

Typically, biomass boilers operate under five modes. These modes include heat-up, slumber mode, normal operation, full flame, and cool down (9).

1) The **heat-up** period occurs when a load is first introduced to a boiler. The thermal mass of the boiler must be heated to temperature before hot water can be supplied to the load.
2) **Slumber mode** is designed to avoid unnecessary re-ignition of a boiler by maintaining a small amount of fuel on the grate when there is no demand from the load. This avoids the unnecessary use of auxiliary power such as electricity when a demand is reintroduced and improves the boiler response time when the load increases.
3) Next, when a boiler is operating under **normal mode** the systems act to burn the appropriate amount of fuel to match the demand. The boiler will fire up and down to match the fluctuations in the demand.
4) During the **full flame** phase the boiler acts at its maximum output to warm the boiler to match the increased supply, both when the load is first introduced and during normal operation.
5) Finally, the **cool-down** period is necessary when a biomass boiler is shut down to avoid damage to the boiler components. This will be explained in more detail later in the report.

Combustion Process

An important part of biomass boiler operation is the combustion process. From the instant the fuel is moved into a biomass boiler to the moment it is removed as ash and particulates it must undergo several key phases. This combustion mechanism can be split into several operations in which key processes are undertaken to ensure successful combustion (10).

1) Before biomass fuel can be burnt efficiently in must undergo a drying period to reduce the moisture content of the fuel and ensure complete combustion. This avoids the formation of slag within a boiler and ensures the fuel burns as intended within the combustion chamber. This process varies depending on the boiler design and the type of fuel that is being used. For example, a moving grate boiler is capable of altering the angle of the grate to cope with different fuel moisture contents.
2) Next, the fuel must go through a devolatilisation phase, which is essential especially for high volatile matter fuels. The process of devolatilisation is necessary to separate any volatile components from the fuel that is to be burnt. The volatiles are then removed as flue gases or water vapour.
3) Once this has been achieved the fuel can go through the combustion process before the remaining ash, particulates and residues are extracted.

2.2. Buffer Vessels

Many biomass boilers require a method of extracting the surplus heat from within a boiler upon shutdown. Once a boiler is shut down a quantity of fuel remains on the boiler grate. The additional fuel must be used to prevent burn back into the fuel store. Failure to reduce the quantity of heat within a boiler and utilise the additional fuel on the boiler grate can result in significant damage to the components of the boiler and reduce its lifetime (11).

A buffer vessel can be used alongside a boiler to extract a proportion of the heat stored within a boiler upon shut down. During the day a buffer vessel will store a volume of cool water in preparation to extract heat from the boiler when the demand from the load is satisfied. When the boiler begins to shut down the excess fuel on the grate must be burnt to prevent burn back. Next, the cooler water stored within the buffer vessel is replaced with the hot water within the boiler and a proportion of the heat stored within the boiler lining. This prevents the water within the boiler from boiling after shutdown and improves system efficiency by capturing any residual heat. It also ensures that the connected heating system does not over heat or over pressurise.

When a demand from the load is re-introduced, usually the following day, the buffer vessel can be used to provide a proportion of the heating demand while the biomass boiler warms to the required flow temperature. This can reduce the need for large auxiliary boilers and increase the cost effectiveness of biomass boiler as an approach to providing hot water to a load.

It is important to consider the heat-up time of the biomass boiler at the start of the day. Typically buffer vessels are only designed to hold a small volume of water. Consequently, the boiler must be given sufficient time to heat before it can contribute towards the load. Additionally, when a thermal store is used in partnership with a biomass boiler a certain proportion of the lower end of the store is designed to function as a buffer vessel.

The size of the buffer vessel is dependent on the properties of the particular biomass boiler used. It is important that the buffer vessel is large enough to extract the appropriate amount of heat from the biomass boiler. The fuel feeding mechanism, the thickness of the boiler lining and the fuel type all influence the buffer vessel size. The formulae in the Tables 2.2.1 and 2.2.2, developed from empirical data by *David Palmer of The Campbell Palmer Partnership Ltd*, were used in the training tool to calculate the volume of the buffer vessels (12). The biomass boiler type and characteristics can be selected in the training tool before the appropriate formulae and turn down ratio are used in the calculations.

Table 2.2.1 (Fuel Moisture Content <=30%)

Boiler Type	Feeding Mechanism	Thermal Lining	Buffer Vessel Equation (l/kW)	Turn Down Ratio
Stoker Burner	Auger	Low	$V = 89.17\Delta T^{-1.0031}$	3.5:1
Stoker Burner	Auger	High	$V = 120.4\Delta T^{-1.0015}$	3:1
Underfed Stoker	Auger	Low	$V = 57.946\Delta T^{-1.006}$	3.5:1
Underfed Stoker	Auger	High	$V = 89.17\Delta T^{-1.0031}$	3:1
Moving Grate	Auger	Low	$V = 202.19\Delta T^{-0.9982}$	3:1
Moving Grate	Auger	High	$V = 371.06\Delta T^{-1.0011}$	2.5:1
Moving Grate	Ram Stoker	Low	$V = 158.27\Delta T^{-0.997}$	3:1
Moving Grate	Ram Stoker	High	$V = 374.1\Delta T^{-1.0009}$	2.5:1

Table 2.2.2 (Fuel Type: Pellets)

Boiler Type	Feeding Mechanism	Thermal Lining	Buffer Vessel Equation (l/kW)	Turn Down Ratio
Stoker Burner	Auger	Low	$V = 223.46\Delta T^{-0.9989}$	4:1
Stoker Burner	Auger	High	$V = 255.64\Delta T^{-1.0002}$	3.5:1
Underfed Stoker	Auger	Low	$V = 57.946\Delta T^{-1.006}$	3.5:1
Underfed Stoker	Auger	High	$V = 130.27\Delta T^{-0.9955}$	3:1
Moving Grate	Auger	Low	$V = 249.53\Delta T^{-1.001}$	3:1
Moving Grate	Auger	High	$V = 463.45\Delta T^{-1.0003}$	2.5:1
Moving Grate	Ram Stoker	Low	$V = 124.62\Delta T^{-0.9991}$	3:1
Moving Grate	Ram Stoker	High	$V = 338.1\Delta T^{-0.9989}$	2.5:1

The formulae above in Table 2.2.1 and 2.2.2 return a value in litres per kW (l/kW). Consequently, multiplying the value given by the rating of the boiler gives the size of the buffer vessel in litres. Currently, the training tool includes formulae for boilers fuelled by pellets or fuel with moisture content of 30% or lower. This could be developed further to include a wider variety of fuel types.

2.3 Thermal Storage

Thermal stores are often used in partnership with biomass boilers to store the surplus hot water produced by a boiler and allow a biomass boiler to be sized as a much lower percentage of the peak-heating load than would otherwise be possible.

Demand Matching

The ability of a thermal store to reduce a biomass boilers size is dependent on the shape of the loads demand profile. A shorter demand profile will allow the boiler to feed the thermal store when the demand is lower than the rating of the boiler. The hot water that is stored while the demand is low can then contribute towards the heating demand when the demand exceeds the rating of the boiler. This is illustrated in the demand profile shown below.

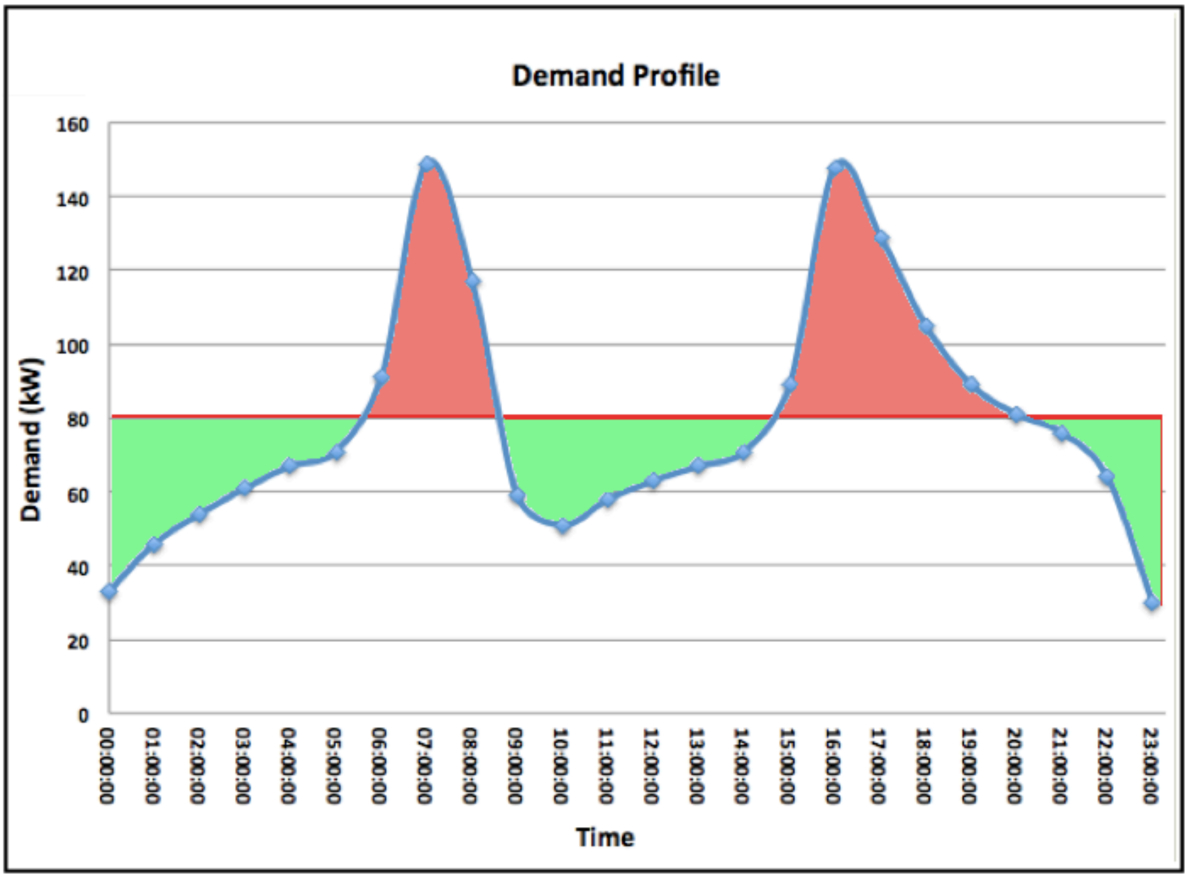


Figure 2.3.1: Example Demand Profile Using A Thermal Store

In this example a demand exists throughout the entire day. However, there are clearly two peaks where the demand increases rapidly. These periods range from approximately 6am-9am and 3pm-8pm. Outside these periods however the demand falls below the maximum output of the biomass boiler, indicated by the horizontal red line. This provides an opportunity for a thermal store to be charged with hot water over night and in the middle of the day. The optimum boiler rating is when the area coloured green in the diagram above is equal to the area shaded in red. The volume of the thermal store must also be large enough to store the hot water generated when the demand from the load is lower than the rating of the boiler.

In this configuration the boiler is firing constantly at its maximum output. This increases the efficiency of the boiler over the year. It also means that the system can react quickly to any change in the demand and removes the need to wait for the biomass boiler to warm before hot water can be provided to the load.

Thermal Store Operation

A thermal store works by maintaining a barrier of hot and cold water. When hot water is pumped into a thermal store a hot interface moves down the length of the store and the quantity of cooler water is reduced. It is essential that mixing between the layers of hot and cooler water within a store be kept to a minimum. For the purpose of this project it has been assumed that the thermal store will benefit from perfect stratification and consequently there will be no mixing between layers in the thermal store.

In reality this may not quite be the case, however it was decided that this was a reasonable assumption for the purpose of the training tool. Typically, sparge pipes are used to reduce the velocity of the hot water as it is injected in the top of the thermal store. These pipes consist of several holes throughout the width of the thermal store to reduce the velocity of each jet of hot water with the aim of reducing the mixing of the water within the store (13).

Typically, there are two main categories of thermal storage, **two-port** and **four-port** thermal stores. Both of these are shown in Figure 2.3.2 below.

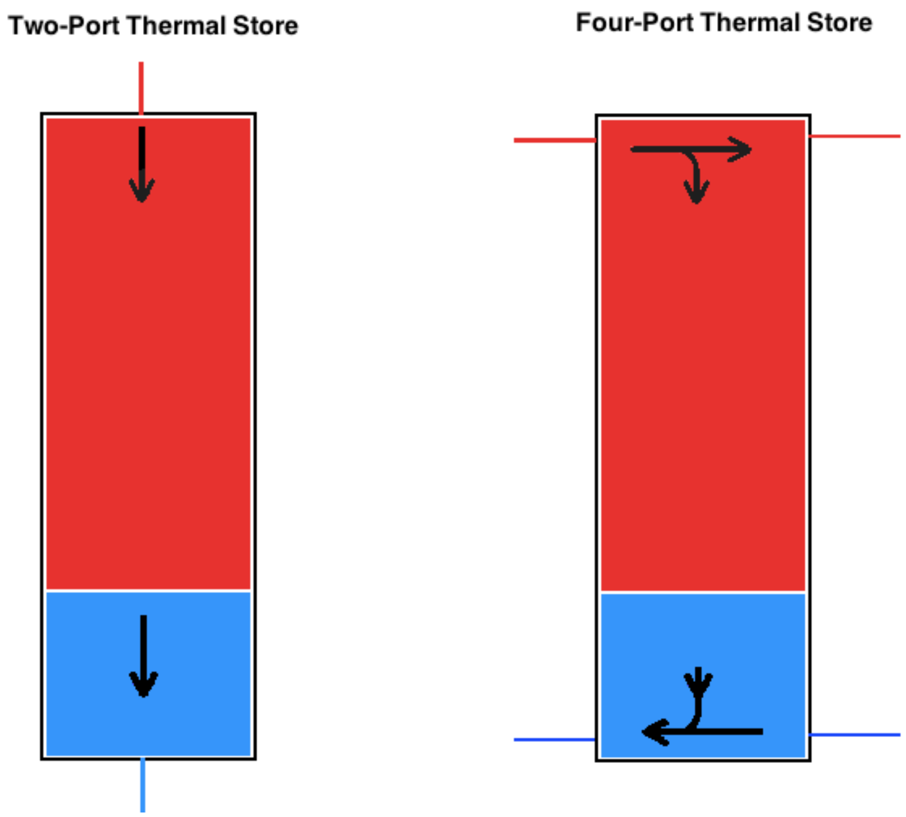


Figure 2.3.2: 2-Port and 4-Port Thermal Stores

Within Figure 2.3.2 the interface between the hot and colder water in the thermal store can be seen as a boundary between the blue and red areas. When there is surplus hot water available from the boiler the red-blue interface will move down towards the bottom of the thermal store. When a demand is introduced to the thermal store, the hot water will begin to empty and the red-blue interface will move upwards.

Two-Port Vs. Four-Port

While two-port and four-port thermal stores are very similar in function there are some significant differences that impact upon the way each design operates and subsequently on the way that the two must be modelled.

When the demand from a load is less than the boiler output and the thermal store is at capacity a 2-port thermal store benefits since there is no direct flow through the store. This reduces the turbulence and mixing within the thermal store. In other words temperature stratification in the store is enhanced since flow through the thermal store is only present when strictly necessary, unlike that through a 4-port thermal store (14).

However, a 2-port thermal store suffers in design when the store has been fully depleted. In this scenario the system pump must be altered to match the biomass boiler output because there is no hydraulic separation between the boiler and the piping network of the heating system. i.e. the system pump must be slowed down to match the biomass boiler flow rate once the thermal store has been depleted (14).

Heat Loss Consideration

Another key consideration is the heat loss associated with thermal stores and buffer vessels. When a boiler is turned off the temperature in the thermal store will fall over time. Over short periods this can be ignored, but there are occasions when the heat loss will be considerable. However, due to the difficulties of accurately modelling the heat losses it was decided to treat the losses as negligible within the training tool.

2.3.1 Thermal Store and Buffer Vessel Control

As previously discussed, a hot water interface moves vertically up and down the length of a thermal store when the store is being charged by a boiler or depleted to feed a load. In practice, temperature sensors are used to establish the position of this hot-cold water interface and hence the quantity of energy held within the thermal store.

These sensors are positioned in various locations up the length of a thermal store so that the control systems can establish the position at which the hot water from the boiler meets the cooler return water from the load.

Typically there are two control schemes used to monitor thermal stores and buffer vessels (15). The first uses two temperature sensors for on-off boiler control, while the second utilises multiple temperature sensors for proportional control of boiler modulation. The position of the first sensors depends on the response time of the particular biomass boiler and the rate at which the thermal store will be depleted at maximum load. If the boiler is capable of responding quickly to changes in demand the sensor will be positioned higher up the thermal store. Similarly, the volume required for a buffer vessel determines the position of the lowest temperature sensor on a thermal store. The purpose of the lowest sensor is to ensure that the boiler is shutdown once the top of the buffer vessel is reach by the hot water from the boiler. Figure 2.3.1 illustrates the position of the temperature sensors for both schemes.

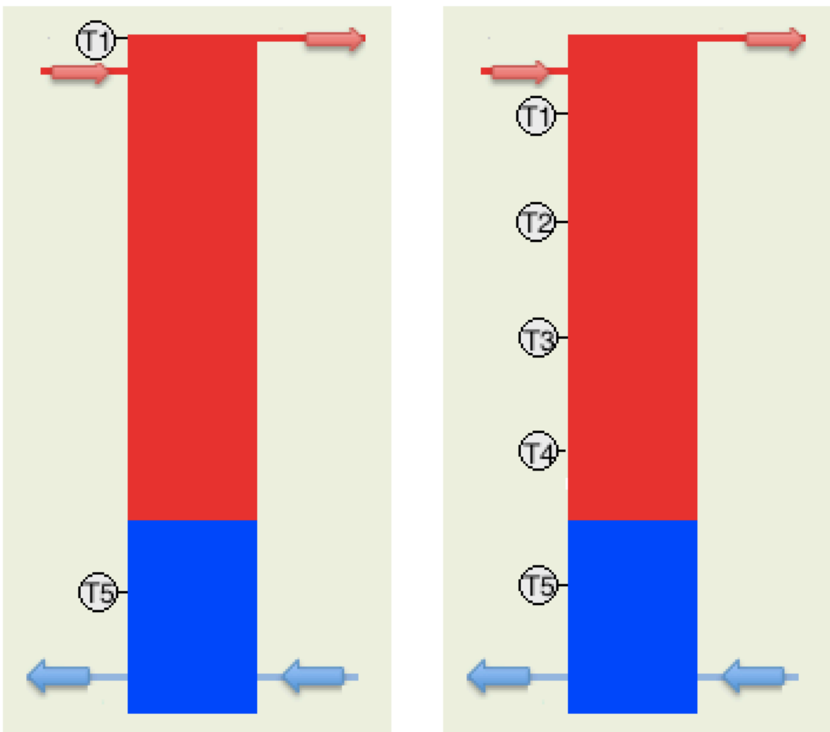


Figure 2.3.1.1: Temperature Sensors on Thermal Stores

2.4 Auxiliary and Back-Up Boilers

It is important to make a clear distinction between auxiliary boilers and back-up boilers. Both are frequently used along side biomass boiler systems to ensure that heating is provided to the load reliably throughout the year. Auxiliary boilers have been included into the training tool so it is important that their role is understood.

Occasionally, whether because of restrictions in space or limitations in budget, even the most intelligently designed biomass boiler systems are unable to provide 100% of the annual heating demand from biomass alone. For this reason the vast majority of biomass boiler systems will include at least one auxiliary boiler. The purpose of an auxiliary boiler is to match the peak heating demand from a load when the biomass boiler system is sized below the peak demand. Typically, these auxiliary boilers are fossil fuelled boilers due to their ability to react quickly to variations in the demand and the relatively cheap capital cost compared to biomass boilers (16).

They are sized based on the difference between the rating of the boiler and the peak heating demand that is expected from a load (16). This is how the auxiliary boilers have been sized within the training tool. For example, if the peak demand from a heating system is 1000kW and the boiler is rated at 700kW, then the auxiliary boiler should be rated at 300kW. An example of an oil fired auxiliary boiler is shown in the diagram below in figure 2.4.1. In this scenario the oil-fired boiler is capable of contributing towards the supply to match the heating requirements when the heating demand is higher than the maximum output of the biomass boiler.

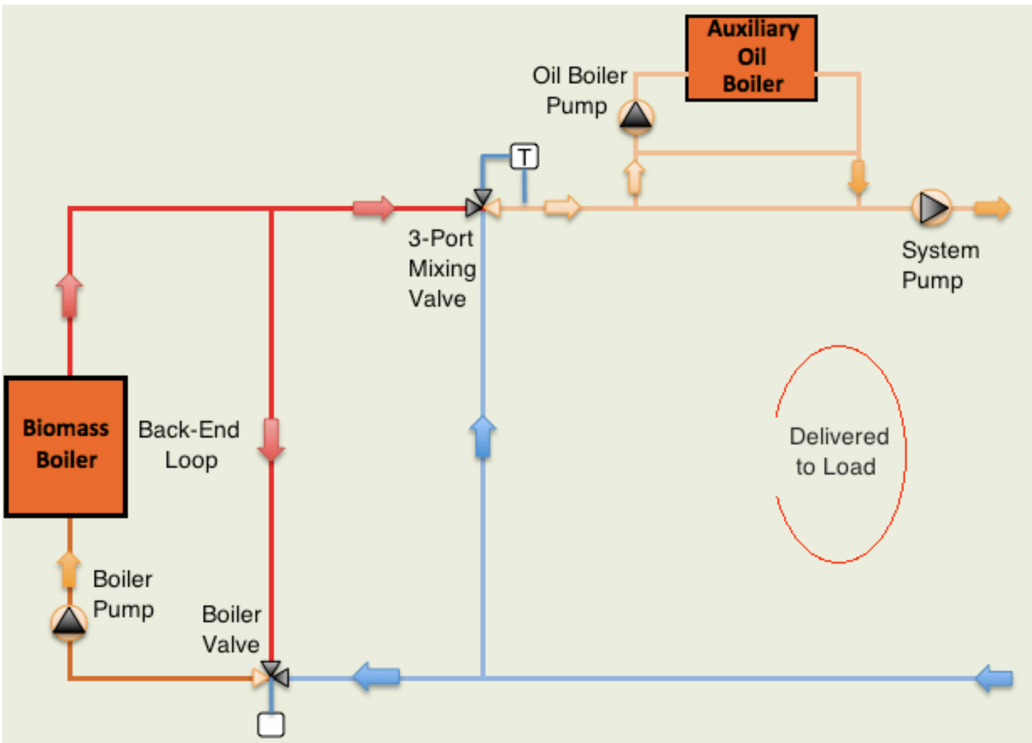


Figure 2.4.1: Biomass System With An Auxiliary Boiler

Contrastingly, back-up boilers are not used as an addition to the systems heating capacity, but instead as a replacement boiler should the biomass boiler system fail. Consequently, backup boilers are normally rated at the peak demand in the scenario that the biomass systems fail completely.

However, in some scenarios a back-up boiler can also operate as an auxiliary boiler on the condition that its turn down ratio is adequate to provide the difference in the biomass boiler rating and the peak demand efficiently.

2.5 Three-Port Mixing Valves

Three-port mixing valves are used in the majority of biomass boiler systems to mix the flow from two pipes into one (17). This is often used when the temperature of the water demanded by the load is lower than the temperature supplied by the boiler. In this scenario the flow from the boiler is usually mixed with the return flow from the load to achieve the desired flow temperature. A temperature sensor on the flow line out to the load is used in practice to control three-port mixing valves. The sensor is used to adjust the flow from each pipe until the desired flow conditions are acquired. This sensor is indicated (T) in Figure 2.5.1 below.

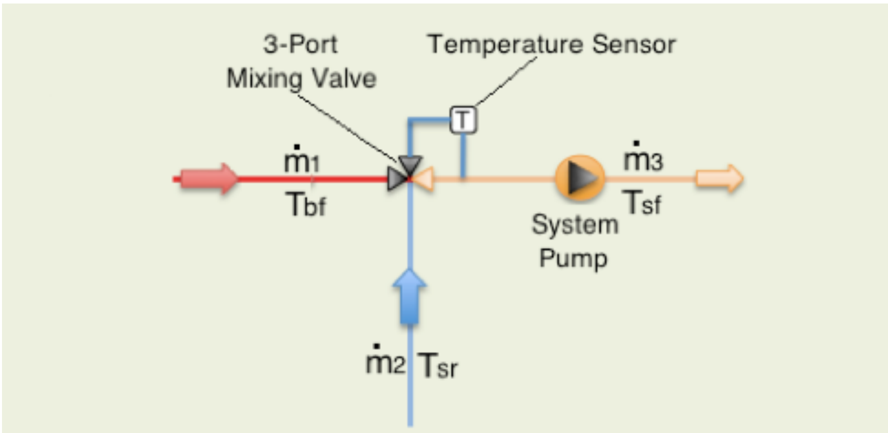


Figure 2.5.1: Diagram of a Three-Port Mixing Valve

If the flow conditions required by the load are known, along with the temperatures of the water from the boiler and returned from the load, then the mass flow rate required from both sides of the three port mixing valve can be found as below.

$$T_{bf}\dot{m}_1 + T_{sr}\dot{m}_2 = T_{sf}\dot{m}_3$$

Substituting $\dot{m}_2 = \dot{m}_3 - \dot{m}_1$ into the equation gives:

$$T_{bf}\dot{m}_1 + T_{sr}(\dot{m}_3 - \dot{m}_1) = T_{sf}\dot{m}_3$$

$$(T_{bf} - T_{sr})\dot{m}_1 + T_{sr}\dot{m}_3 = T_{sf}\dot{m}_3$$

And finally, re-arranging the equation above gives the mass flow rate of the hot water from the boiler.

$$\dot{m}_1 = \frac{T_{sf}\dot{m}_3 - T_{sr}\dot{m}_3}{(T_{bf} - T_{sr})} \qquad equation\ 2.5.1$$

Once the mass flow rate from the boiler is known, then the mass flow rate required from the load return is simply $\dot{m}_2 = \dot{m}_3 - \dot{m}_1$. The equations shown above are used within the training tool for each piping configuration to find the proportion of hot water required from the boiler and the proportion of cooler water re-circulated from the load.

3. Training Tool Development

In this section of the report the simultaneous equations that have been developed to model each configuration included in the training tool are explained. Additionally, the key parameters that govern the operation of each of the biomass boiler configuration are detailed.

3.1 Key Parameters

While the training tool will calculate the flow rates and temperatures throughout each system, the results are dependent on a number of key parameters and assumptions.

The first key parameters for each configuration are those related to the biomass boiler and the back-end loop. The back end loop is designed to return a certain proportion of the flow from the boiler directly back to the boiler to prevent the return temperature from the load being too low.

The manufacturer of any specific biomass boiler will usually specify a minimum boiler return temperature. If the return temperature falls below this value then the boiler can be damaged internally. Consequently, the boiler flow and return temperatures are of importance as well as the back end valve opening percentage and the boiler pump flow rate. These parameters are shown in Figure 3.1.1 below where T_{bw} is the temperature difference across the boiler while the dotted lines illustrate the pipework to the rest of the boiler system and out to the heating load.

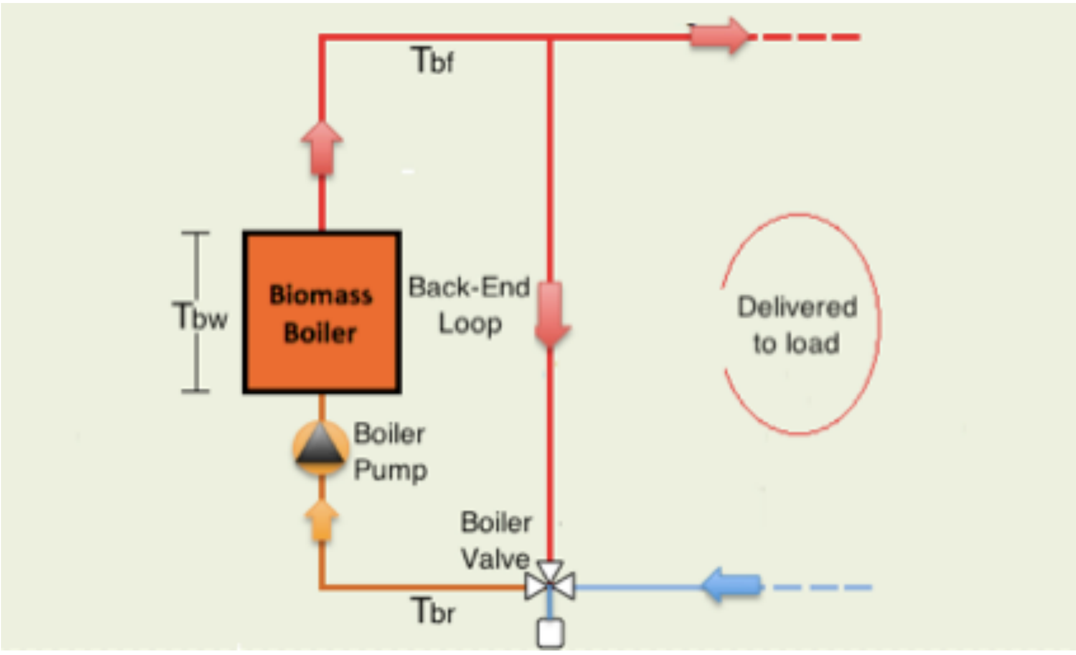


Figure 3.1.1: Diagram of a Biomass Boiler Back-End Loop

Next, the parameters that determine the load side of a biomass boiler system must be considered carefully. This includes the load mixing valve opening percentage, the system pump flow rate, and the load flow and return temperatures. This is indicated in the diagram below where T_{ls} is the temperature of the water to the load and T_{lr} is the temperature of the water returned by the load.

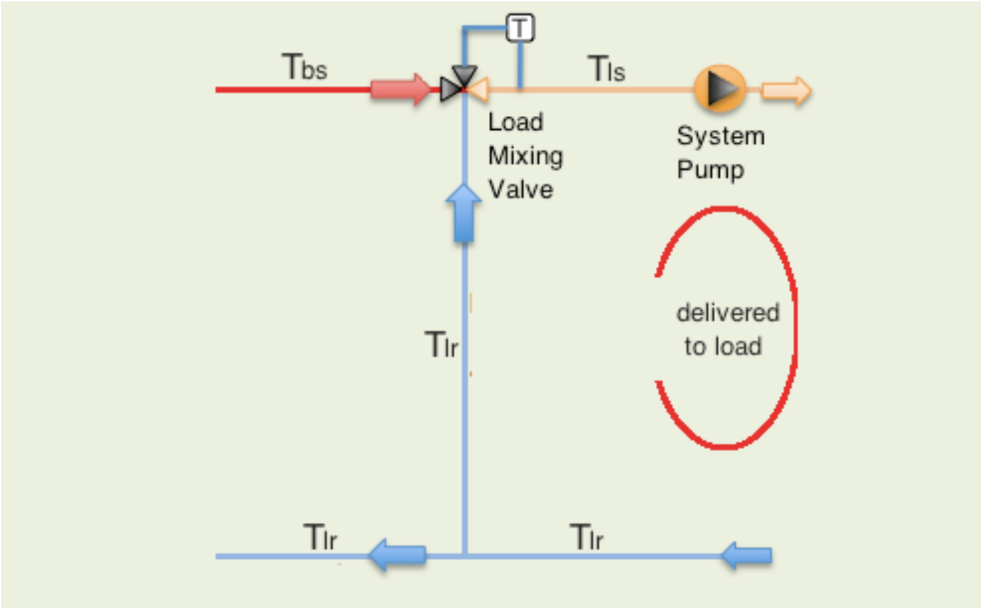


Figure 3.1.2: Diagram of the Load Side of a Biomass Boiler System

The equations used to model the load-mixing valve in the training tool were detailed previously in section 2.5 of the report. Similarly, the equations governing the flow conditions around the back-end loop of the biomass configurations are explained later in the report in section 3.3.1.

Demand Profile Linear Interpolation

The demand profiles that were created for inclusion in the training tool and later as part of the case study, gave hourly data for a 24-hour period. However, the training tool operates on a five-minute time scale. To compensate for this, the tool linearly interpolates the demand profile values for each five-minute time step between the hourly values. It was decided that this is a more accurate and life like method of modelling the demand profiles than repeating the values given throughout the course of each hour.

3.2 Boiler Heat-Up and Cool-Down Profiles

It is important that each of the configurations that are modelled within the training tool include a boiler heat-up and cool-down profile. This section of the report looks at the theory behind each and the way in which they have been modelled within the training tool.

3.2.1 Boiler Heat-Up

Before a biomass boiler is capable of satisfying a load, the water within the boiler must be heated to flow temperature. Additionally, the thermal mass of the boiler itself must be heated up to temperature. This includes the thermal lining and the inner components of the boiler.

Depending on the type of boiler, this can be a significant length of time. The thickness of the thermal lining, the fuel type and boiler rating all influence the time required to heat the flow to operating temperature. For this reason all of these characteristics are included as variables within the training tool.

Modelling Procedure

The modelling procedure is split into two segments within the training tool. The procedure considers:

1) The length of time for the boilers refractory lining to heat to its operating temperature.
2) The time taken to heat the volume of water held within the boiler to the boiler supply temperature.

Both of these factors are taken into consideration simultaneously since the water held within the boiler will warm while the boilers refractory lining heats. However, the two processes happen at different rates due to the construction and design of biomass boilers. When the heat-up process first begins the thermal lining will "steal" most of the energy when it is relatively cool, and then, as it warms up, the heat exchanger containing the water will receive more of the energy. Consequently, the temperature increase of the water from the boiler will not be linear, rather an initial period of slow warming, followed by a fairly rapid ramp up to the boiler set point temperature.

This is taken into account by rationing the heat input from the boiler between the refractory lining and the water. As the refractory lining heats, and the temperature difference falls, the heat input to the thermal lining (kW) will reduce. Consequently, a larger proportion of the energy will be made available to heat the volume of water flowing within the heat exchanger as the thermal lining gets warmer. Given data on the mass of the boilers refractory lining and the volume of water held within the boiler the heat-up periods of both can be estimated.

The tool establishes the volume of water held within each boiler as a function of the boilers rating and its volume ratio. The **volume ratio** of the biomass boilers was used to determine the volume of water held within each boiler (18). The volume ratio is available as a variable that the user can alter if desired.

The volume of water heated by a boiler is equal to the volume ratio multiplied by the rating of the boiler. Once this volume of water is established, the time taken to heat that volume of water up to the set-point temperature can be calculated using Equation 3.2.1.1. The same equation is used to calculate the time for the thermal lining to heat, where the volume of water is replaced with the mass of the refractory lining.

$$Time\ (hrs) = \frac{V.(T_t - T_o).Cp}{Boiler\ Input\ (kW) \times 3600} \qquad equation\ 3.2.1.1$$

However, the heat input from the boiler will vary as the refractory lining of the boiler heats. At first the boiler input will only be a fraction of the rating of the boiler but, as the thermal lining warms, the heat input to the water will increase. This is illustrated in an example calculation below where the boiler characteristics are listed in table 3.2.1.2 and the calculation process is visible in table 3.2.1.1.

Table 3.2.1.1: Boiler Heat-Up Calculation Process

Refractory Lining

Lining Temp (°C)	Heat Input (W)	Time to Heat
10	70000	00:02:23
50	66111	00:03:09
100	62222	00:03:21
150	58333	00:03:34
200	54444	00:03:50
250	50556	00:04:07
300	46667	00:04:28
350	42778	00:04:52
400	38889	00:05:21
450	35000	00:05:57
500	31111	00:06:42
550	27222	00:07:39
600	23333	00:08:56
650	19444	00:10:43
700	15556	00:13:24
750	11667	00:17:51
800	7778	
	Total Time	01:46:17
	Rounded	01:45:00

Volume of Water

Time to Heat	Water Temp (°C)	Total Time
00:02:23	10.28	00:02:23
00:03:09	10.95	00:05:32
00:03:21	11.97	00:08:53
00:03:34	13.39	00:12:27
00:03:50	15.27	00:16:17
00:04:07	17.68	00:20:24
00:04:28	20.69	00:24:52
00:04:52	24.44	00:29:44
00:05:21	29.06	00:35:05
00:05:57	34.74	00:41:03
00:06:42	41.75	00:47:44
00:07:39	50.48	00:55:24
00:08:56	61.49	01:04:19
00:10:43	75.70	01:15:02
00:07:01	85.00	01:22:03
00:00:00	85.00	01:22:03
00:00:00	85.00	01:22:03
	Time to Heat	01:22:03
	Rounded	01:20:00

Table 3.2.1.2: Boiler Heat-Up Characteristics

	Boiler Rating (W)	75000
	Refractory	Water
Heat Input @To (W)	70000	5000
Mass(kg)	250	600
Cp (J/kg)	1000	4190
To (°C)	10	10
Tt (°C)	800	85

From table 3.2.1.1, it can be observed that the heat input into the refractory lining decreases as it warms from its initial temperature to the temperature of the flame. This increases the quantity of heat input available to the volume of water, increases the rate at which the water heats. Both the refractory lining and the water heats simultaneously. In this example, the water reaches its target temperature (85°C) after 1 hour and 22 minutes, while the refractory lining reaches its maximum temperature after 1 hour and 46 minutes.

These lengths of time are rounded to the nearest five-minute time interval in the training tool as indicated in table 3.2.1.1. The temperature progression of the water from the boiler around the back-end loop is then modelled exponentially over the calculated time period. The heat-up period is made visible to the user of the tool within the table of results for each biomass boiler configuration.

In table 3.2.1.1, the 'Time to Heat' column on the left is calculated by considering the heat input from the boiler and the temperature increase from the starting temperature (To = 10°C) to the next temperature below in the table (50°C). Equation 3.2.1.1 is used to calculate the time period for each row down the table until the refractory lining has reached its operating temperature of 800°C.

As the refractory lining warms so does the water inside the heat exchanger. At the start of the heat-up period it has been assumed that the thermal lining will 'steal' the majority of the heat input from the combustion chamber, while the water within the heat exchanger will receive the rest. In this example the thermal lining receives 70kW of heat input from the 75kW boiler leaving 5kW of heat input to the water. As the temperature difference between the flame and the thermal lining decreases so does the heat input from the boiler, which increases the energy made available to the water.

To calculate the water temperature after each time step, equation 3.2.1.1 was re-arranged to give equation 3.2.1.2 as below, where the heat input is equal to the boiler rating minus the heat input to the thermal lining during that particular time step.

$$Tt = \frac{To + (t \times Heat\ Input) \times 3600}{Volume \times Cp} \qquad equation\ 3.2.1.2$$

Figure 3.2.1.1 shows how the temperature of the water increases during the heat-up phase, while Figure 3.2.1.2 illustrates how the temperature of the thermal lining increases with respects to time.

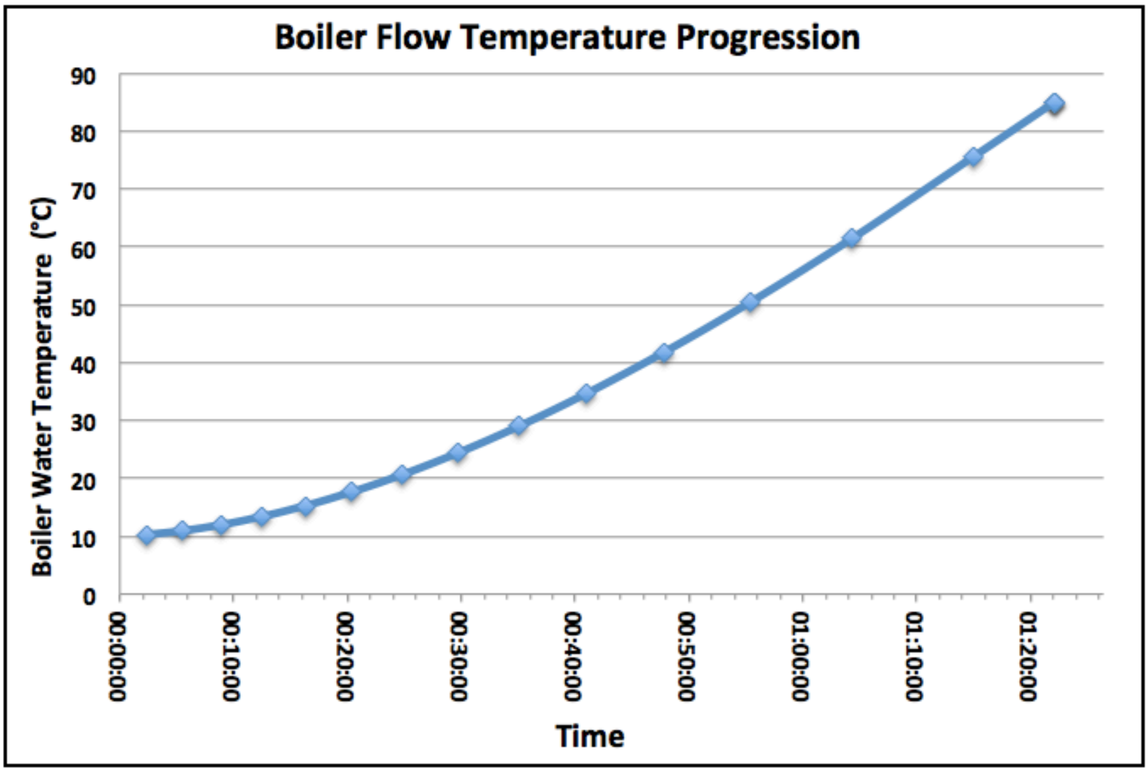


Figure 3.2.1.1: Boiler Water Temperature Progression

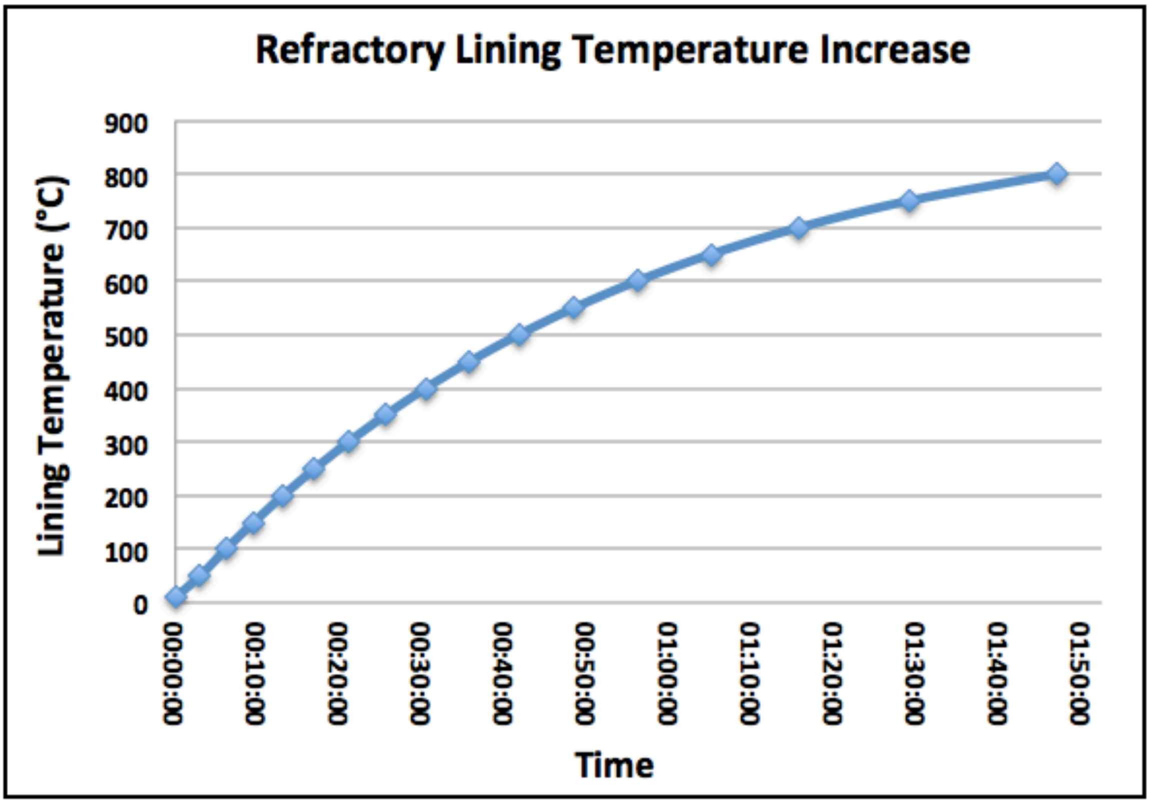


Figure 3.2.1.2: Thermal Lining Temperature Progression

Figure 3.2.1.1 demonstrates an initial period of slow heating, followed by a rapid increase towards the boiler set-point temperature. Figure 3.2.1.2 also illustrates how the heat input to the refractory lining decreases as it nears its maximum temperature and the temperature increase slows.

In this simple example, it has taken 01:20:00 for the water to heat to the required temperature. By including this representation of the heat-up period into the training tool the user can appreciate the importance of ignited a biomass boiler with enough time before the load is introduced. Otherwise, the load may go without heating for a significant length of time.

It is important to stress that this modelling procedure is an estimation of a biomass boiler heat-up period and, without further detailed information on the exact processes present while a biomass boiler heats-up, it is difficult to establish a more accurate representation. However, this method takes into account the important factors associated with a boiler heat-up period, which adds to the value of the training tool. To develop the training tool further it would be valuable to develop accurate heat-up profiles for different types of biomass boilers and include them into the modelling process. However, as a training tool, this representation of a biomass boiler heat-up profile is useful to demonstrate how the water temperature progresses when a load is first introduce to a boiler.

3.2.2. Boiler Cool-Down

The training tool also includes a representation of a biomass boiler during the cool-down phase. The cool down period of a biomass boiler is of equal importance, particularly when modelling the use of a buffer vessel. The volume required by the buffer vessel is determined by the amount of heat that must be extracted from each boiler type upon shutdown. The equations used to calculate the buffer vessel volume are shown in section 2.2.

The time taken for a biomass boiler to cool down to an acceptable internal temperature is determined by the cool down profile of the particular boiler. This proved to be a challenging part of the modelling to establish, particularly without specific information on the operation of individual boilers.

For example, when a biomass boiler is shutdown a quantity of fuel, which needs to be burnt, remains on the grate. This quantity of fuel depends on the boiler type and size. Finally, a basic estimation was made to represent the cool-down profiles for each biomass boiler.

The training tool assumes that the cool-down period is equal to the time is takes to replace the volume of cooler water held within the buffer vessel with hot water from the boiler, while maintaining the minimum return temperature to the boiler, by diverting a proportion of the flow down the back-end loop. Once the buffer vessel is charged, the boiler is deemed to be "safe" and will then cool down towards ambient over night, with heat being lost mainly up the flue.

3.3 Biomass Boiler Configurations Explained

Within this section of the report the key principles and operation of each of the configurations modelled in the training tool is explained in detail. The various configurations behave differently from one another throughout the course of the day so each must be analysed individually to ensure that any assumptions that are made for the analysis of one configuration is appropriate for another.

3.3.1. Biomass Boiler with Back-End Valve and a Three-Port Mixing Valve

This is the first and most basic of the configurations that will be examined within this project. This system is only capable of providing heating up to the capacity of the biomass boiler i.e. there is no form of storage. This means that the boiler must be sized based on a high percentage of the peak-heating load. Additionally, this configuration does not include any form of buffering to allow the boiler to cool upon shutdown. For the purpose of this configuration it is assumed that the biomass boiler does not require a cool-down period. In reality this is unlikely to be the case. Figure 3.3.1.1 below shows the piping layout for this configuration.

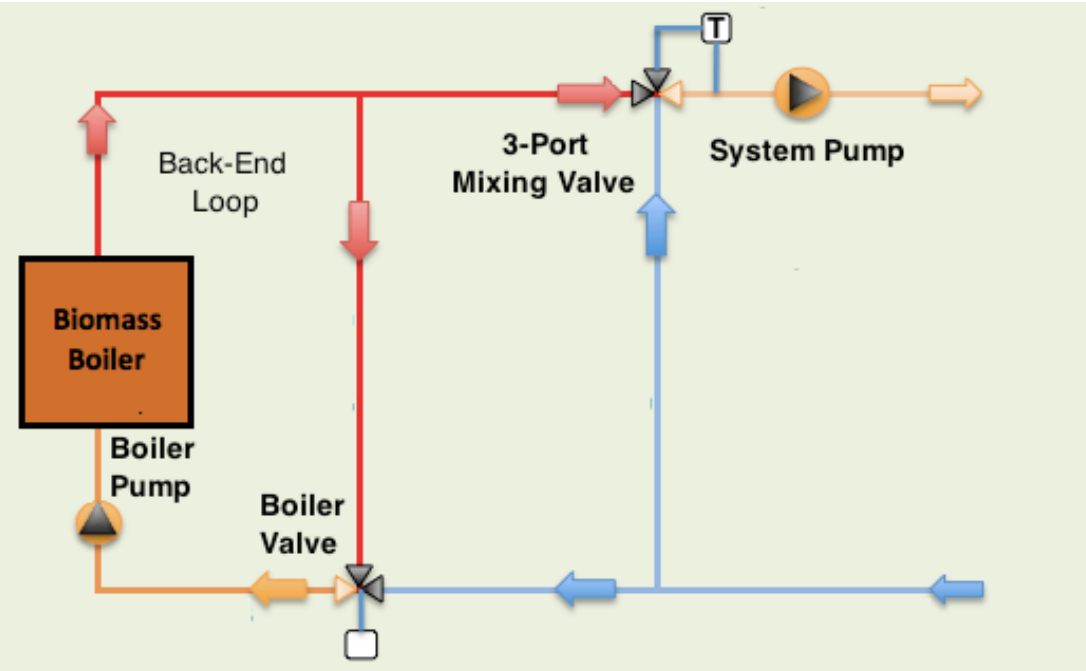


Figure 3.3.1.1: Biomass Boiler with Back-End Valve and a Three Port Mixing Valve

3.3.1.1 System Operation

Initially, the boiler will start to warm when a demand is introduced to the system. However, as previously discussed there is a heat-up period associated with a biomass boiler when started from cold. During this period the flow will circulate around the back–end loop only until the temperature of the water from the boiler is up to the required temperature. The progression of the flow temperature during boiler heat up is modelled in the training tool using the method and assumptions detailed in section 3.2 of this report. Once the boiler has heated the flow to the appropriate temperature, a proportion of the flow is diverted from the back-end loop to feed the load. This supply is mixed with the cooler return flow from the load using a 3-port mixing valve to acquire the required flow temperature to the load (19). In practice the correct flow rate from both pipes is acquired using a temperature sensor, which is part of the 3-port mixing valve. If the flow out to the load is too high then the valve will adjust to allow less hot water from the boiler through while increasing the proportion of cooler water from the return.

Supply Flow Dilution

When the demand from the load is larger than the rating of the biomass boiler, the temperature of the water provided to the load begins to fall below the required system flow temperature. This is because it is important to ensure that the return temperature to the boiler is above the minimum return temperature.

Consequently, the flow rate through the back-end loop of the system will have a minimum value to ensure that the boiler return temperature is above the minimum temperature permitted by the boiler. When the demand increases above the rating of the boiler the return of cooler water directed towards to the boiler valve will increase. To compensate, a larger proportion of the flow is diverted from the system return towards the 3-port mixing valve and the temperature of the water out to the load will begin to fall.

Eventually, this will reduce the temperature of the water returned by the load. As this happens and the demand increases, the flow down the back-end loop will increase to protect the boiler from the cooler return flow, while the return flow diverted towards the 3-port mixing valve will increase and the supply of hot water from the boiler will reduce. This will result in the temperature of the flow supplied to the load and the return water from the load decreasing in temperature further.

Once the demand from the load falls below the rating of the boiler the temperatures of the water supplied and returned by the load will begin to recover up towards the design system supply and return temperatures. The time is takes for this to happen is dependent on the design of the attached heating system, such as the piping length of the load.

3.3.1.2 System Governing Equations

This section of the report will detail the equations that have been used to model the first configuration modelled within the training tool. The equations have been used while considering the system operation in an attempt to accurately model the piping configuration within the training tool.

Figure 3.3.1.2 below illustrates the calculation procedure used to evaluate this particular biomass boiler system. The exact procedure is complicated and depends heavily on the condition of the system at any given time interval. The boxes in orange are parameters chosen by the user, while the boxes in blue are calculated from the parameters that have been selected.

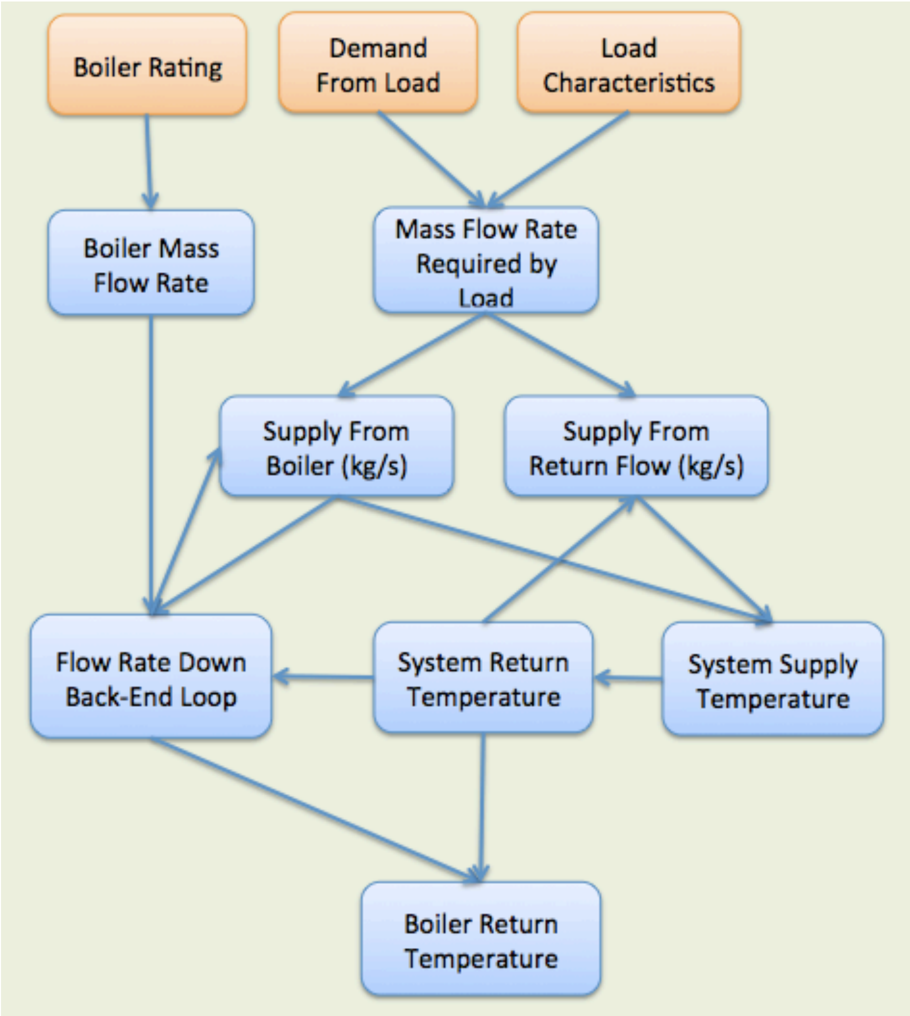


Figure 3.3.1.2: Flow Chart of Calculation Process

From the boiler and load characteristics the conditions throughout the piping network can be calculated. It can be observed in figure 3.3.1.2 that some values are dependent on several other values within the system. For example, flow rate down the back-end loop of the system is dependent on the following characteristics:

- Load return temperature, boiler mass flow rate, flow rate supplied to the load directly from the boiler.

If the system return temperature starts to fall then the flow rate down the back-end loop will increase to protect the boiler from a reduced return temperature. This will in turn reduce the flow available directly to the load and the temperature supplied to the load will begin to drop. This describes the process of flow dilution previously mentioned. This process, and the equations used to calculate the conditions throughout the piping configuration, is explained further throughout this section of the report.

Boiler Back-End Loop

It is important that the return temperature to a biomass boiler remains above a minimum temperature while the boiler is operating. There is a maximum permitted temperature drop across all biomass boilers. If the return flow to the boiler is below the minimum return temperature then the boiler will be incapable of heating the water up to the required flow temperature and the boiler may be damaged. To ensure that this is not the case, a minimum back end loop flow rate can be found for the system. To calculate this value, the boiler mass flow rate along with the return temperature from the load and the boiler flow temperature is required. To find the mass flow rate from the boiler, equation 3.3.1.2.1 was used.

$$m_b = \frac{Boiler\ Rating\ (kW)}{Cp \times \Delta Tb} \qquad equatin\ 3.3.1.2.1$$

From this, the boiler flow temperature, and the return temperature from the load, the minimum flow rate through the back end loop can be found to ensure that the maximum temperature drop across the boiler is not exceeded. These valves are indicated in Figure 3.3.1.3 below where x is the mass flow rate from the boiler, y is the flow down the back-end loop, and z is the flow rate from and too the load.

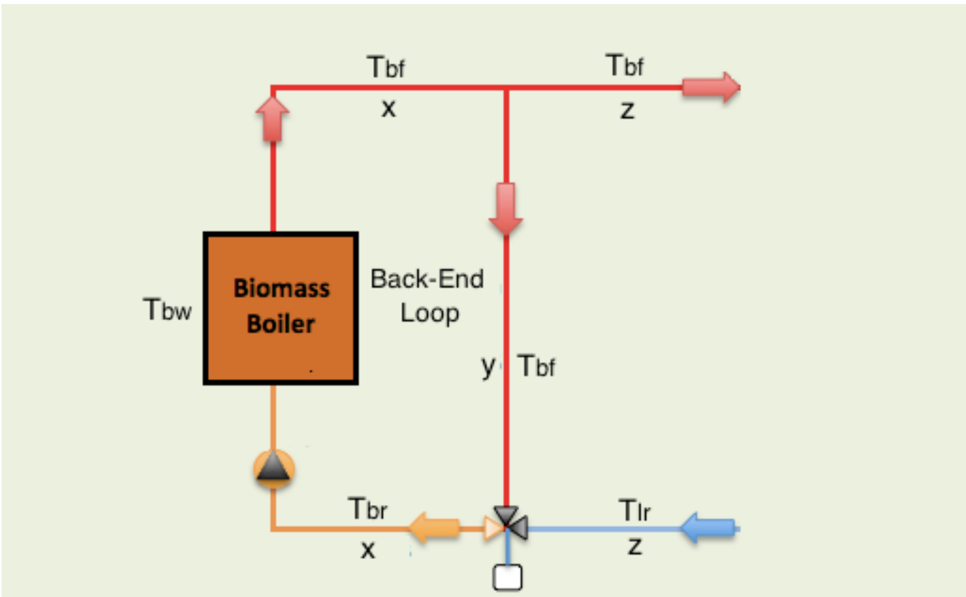


Figure 3.3.1.3: Diagram of a Biomass Boiler Back-End Loop

And so, the minimum flow through the back end loop is calculated as follows.

$$T_{bf}y + T_{lr}z = T_{br}x$$

And knowing that z = x – y the equation becomes:

$$T_{bf}y + T_{lr}(x - y) = T_{br}x$$

$$(T_{br} - T_{lr})y = (T_{br} - T_{lr})x$$

And so,

$$y = flow\ rate\ down\ back\ end\ loop = \frac{(T_{br} - T_{lr})}{(T_{bf} - T_{lr})}x \qquad equation\ 3.3.1.2.2$$

It is important that this value is not exceeded. Consequently, if the return temperature from the load begins to fall this will be reflected in the equation and the flow down the back end loop will increase and the supply of hot water to the load will decrease. Subsequently, in this configuration the maximum flow of hot water available to the load is equal to the mass flow rate of the boiler minus the minimum flow down the back-end loop.

Load Side Requirements

The next consideration when modelling this first configuration is the mass flow rate required by the load. This will determine the flow demanded directly from the boiler and the quantity of cooler water recycled from the load return.

Provided that the supply and return temperatures to and from the load are known along with the demand (kW) the required mass flow rate to the load can be found using Equation 3.3.1.2.3 below:

$$\dot{m}_l = \frac{Demand\ from\ Load\ (kW)}{Cp \times \Delta T_l} \qquad equation\ 3.3.1.2.3$$

Knowing that the mass flow rate to the load is provided using a combination of the hot water directly from the boiler and a proportion of the colder water returned from the load the proportion of each can be calculated. These two supplies are combined using the load-mixing valve seen in the diagram 3.3.1.1.

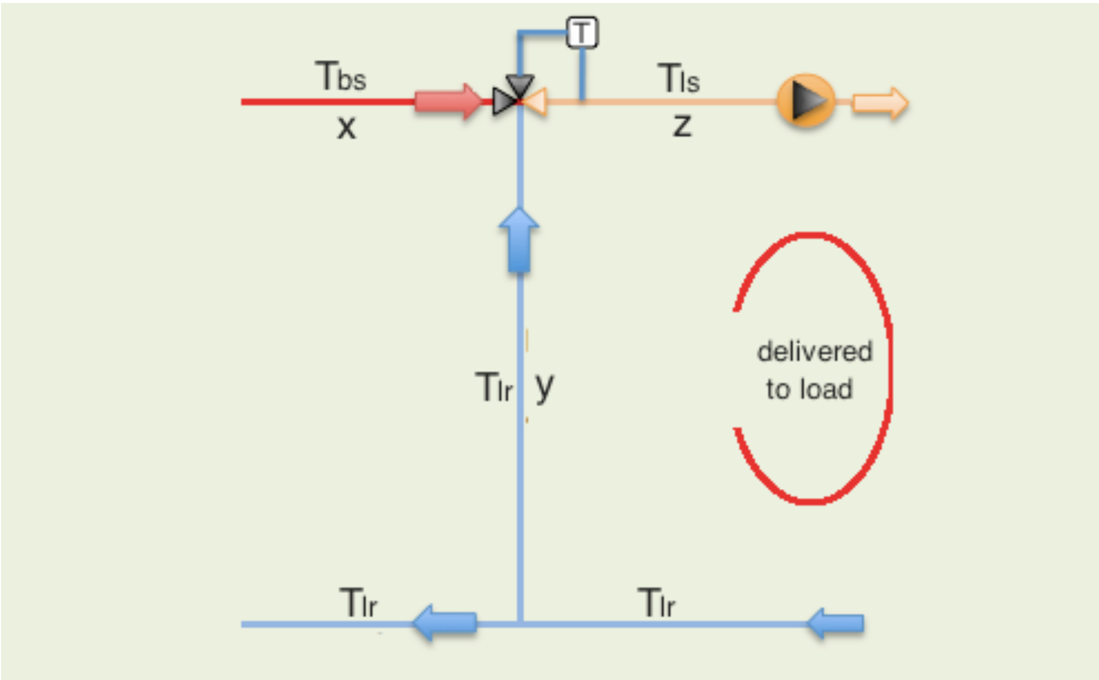


Figure 3.3.1.4: Diagram of a Biomass Boiler Load Side

$T_{bs} = Temperature\ \ of\ boiler\ supply$

$T_{lr} = Temperature\ of\ load\ return\ flow$

$T_{ls} = Temperature\ of\ water\ demanded\ by\ load$

If the mass flow rate directly from the boiler is given the symbol 'x' and the supply from the returning colder water is equal to 'y' then the flow rate to the load 'z' is equal to x + y = z. This can be seen in Figure 3.3.1.4 above. And so the flow rate directly from the boiler 'x' can be found as follows:

$$T_{bs}(x) + T_{lr}(y) = T_{ls}(z)$$

Substituting $y = z - x$ into the equation above gives:

$$T_{bs}(x) + T_{lr}(z - x) = T_{ls}(z)$$

$$T_{bs}(x) - T_{lr}(x) = T_{ls}(z) - T_{lr}(z)$$

$$(T_{bs} - T_{lr})x = (T_{ls} - T_{lr})z$$

And so the mass flow rate demanded directly from the boiler (x) at temperature T_{bs} is equal to:

$$x = \frac{(T_{ls} - T_{lr})}{(T_{bs} - T_{lr})} z \qquad equation\ 3.3.1.2.4$$

Provided that the temperature demanded and returned by the load is known, along with the temperature of the water from the boiler, the flow rates can be found. Finally, from this the water recycled from the system return is equal to y = z – x.

Flow Temperatures

As previously discussed, when the demand from the load exceeds the rating of the boiler the temperature of the supply to the load will start to fall as it becomes diluted with the cooler load return flow. This is because a larger proportion of the return from the load is re-circulated to prevent the boiler return flow from falling below the minimum boiler return temperature. Modelling this in the training tool proved difficult due to the assumption that must be made and the unknown characteristics associated with the load.

In the training tool it is assumed that the flow out to the load is returned during the next five-minute time step. Consequently, changes in the demand are almost instantly reflected in the return flow within the training tool. However, in reality the length of time it will take for the water to circulate the load is dependent on the length of the piping. For example, the effects of increasing the demand above the rating of a biomass boiler system will not be seen in the return temperature as quickly in a district heating network as it would for a single building.

The return temperature from the previous five-minute time step was used to calculate the temperature of the water supplied to the load. If the demand from the load was smaller than the rating of the boiler then the flow temperature will equal the flow temperature demanded by the load.

However, if the demand increases above the rating of the boiler, then a higher proportion of the return water will be recycled to the load, to ensure that the boiler return temperature remains above the minimum return temperature permitted. Consequently, the return temperature from the load will also fall below the initial load return temperature. This is why the return temperature from the previous five-minute time step was used to calculate the temperature of the flow to the load when the demand is higher than the boiler rating.

Equation 3.3.1.2.5 was used to model this scenario into the training tool, where $T_{lr(-5mins)}$ is the temperature of the water returned by the load during the previous five minute time step.

$$T_{ls} = \frac{(\dot{m}_{bs} \times T_{bs}) + (\dot{m}_{lr} \times T_{lr(-5mins)})}{(\dot{m}_{bs} - \dot{m}_{lr})} \qquad equation\ 3.3.1.2.5$$

Similarly, the return temperature to the boiler (T_{br}) is found by combining the flow from the back end loop ($\dot{m}_{bl}$) and the flow returned by the load to the back-end valve ($\dot{m}_{lrb}$) as indicated in Figure 3.3.1.3. The return temperature to the boiler is found my averaging the two temperatures considering the mass flow rate of each as seen in Equation 3.3.1.2.6 below:

$$T_{br} = \frac{(T_{bs} \times \dot{m}_{bl}) + (T_{lr} \times \dot{m}_{lrb})}{(\dot{m}_{bl} + \dot{m}_{lrb})} \qquad equation\ 3.3.1.2.6$$

Table 3.3.1.2 below illustrates how the temperature of the supply and return flow varies as the load increases above the rating of the biomass boiler. The colour scheme is used within the training tool to indicate this process to the user.

The table shows how the boiler heats the flow up to temperature, in this case 85°C, before providing the load with hot water, while ensuring a minimum boiler return temperature. The diagram also indicates how the supply and return temperature too and from the load falls (from green to red) as the demand increases above the rating of the biomass boiler.

Table 3.3.1.2: Table of System Flow Temperatures

Boiler Tf (°C)	Boiler Tr (°C)	System Tf (°C)	System Tr (°C)
10.0	NA	NA	NA
10.0	NA	NA	NA
10.0	NA	NA	NA
10.0	NA	NA	NA
10.0	NA	NA	NA
10.0	NA	NA	NA
10.0	NA	NA	NA
10.0	10.0	NA	NA
18.9	18.9	NA	NA
27.9	27.9	NA	NA
36.8	36.8	NA	NA
45.7	45.7	NA	NA
54.6	54.6	NA	NA
63.6	63.6	NA	NA
72.5	72.5	NA	NA
81.4	81.4	NA	NA
85.0	76.6	50.0	30.0
85.0	75.6	50.0	30.0
85.0	70.0	42.6	22.6
85.0	70.0	34.9	14.9
85.0	70.0	26.9	10.0
85.0	70.0	21.7	10.0
85.0	70.0	21.4	10.0

The work done by the boiler is dependent on the return temperature to the boiler since the mass flow rate from the boiler will remain constant. Consequently, the work done by the boiler is found using the Equation 3.3.1.2.7 seen below:

$$Boiler\ Work = \dot{m}_b \times Cp \times \Delta T_b \qquad equation\ 3.3.1.2.7$$

Boiler Turndown Ratio

Another important factor that must be considered is the performance of the configuration when the demand from the load is below the minimum output of the boiler. In this scenario the biomass boiler system will be incapable of providing the load with the hot water it requires. This is partially why a buffer vessel or thermal store is so important. It provides a store of hot water that can be used to match the load when the demand is below the turndown ratio of the biomass boiler. For this reason it can be recommended that some form of buffering is a minimum requirement for a biomass boiler system. The operation of a biomass boiler system with a buffer vessel is explained in the next section of this report.

The turn down ratio is selected in the training tool using the characteristics of the biomass boiler that has been selected. However, the training tool does not include a minimum boiler output into the calculation process.

In reality, when the demand from the load is below the minimum output of a biomass boiler the supply will be removed and the boiler will operate in slumber mode until the load increases. The load will then recognise that the demand has not been matched and the demand from the load will increase to account for the time in which the load was not satisfied.

Once the demand from the load is above the minimum output of the boiler, the supply will be reintroduce providing hot water to the load once again. Unfortunately, this is very difficult to model in Excel without specific information about the behaviour and characteristics of the load. It also involves iterations with the demand profile values in the spreadsheet. For the purpose of the training tool it was decided that this is too complicated and far too time consuming to model accurately.

For these reasons, the turn-down ratio of the biomass boiler were ignored in the calculations and it was assumed that the boiler would provide the load with hot water regardless of how small the demand may be. However, the training tool provides system feedback, by calculating the percentage of the day that the load is satisfied. This feedback takes into account the time in which the demand is below the turndown ratio of the boiler. When the demand is below the minimum output of the boiler the load is considered to be not satisfied. This feedback demonstrates to the user the importance of the boiler turndown ratio and the impact it can have. More detail is available later within section 4.2 of this report.

3.3.2. BB with Back-End Valve, Buffer Vessel, and a Three-Port Mixing Valve

The next configuration considered within the training tool includes a buffer vessel to protect the biomass boiler upon shut down. The system is designed to store a volume of cool water throughout the course of the day to absorb the heat stored within the biomass boiler when the demand from the load is removed. Figure 3.3.2.1 below displays a typical biomass boiler system that includes a buffer vessel and a three-port mixing valve.

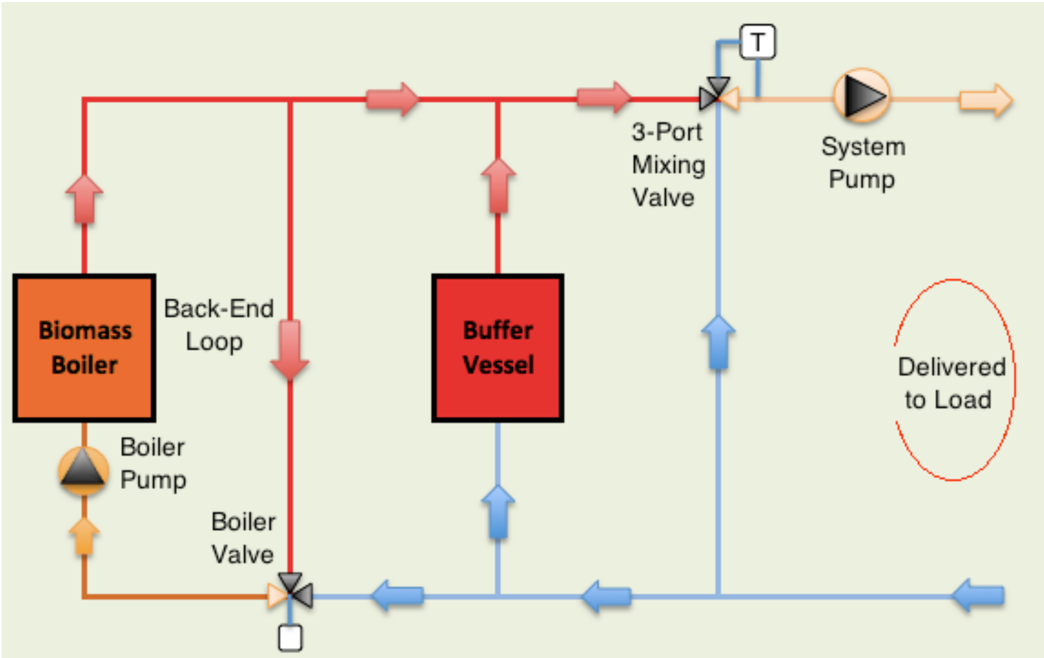


Figure 3.3.2.1: Biomass Boiler with Back-End Valve, Buffer vessel, and a Three-Port Mixing Valve

3.3.2.1. System Operation

The operation of this piping configuration is very similar to the first configuration but with the addition of the buffer vessel. The buffer vessel can contribute towards the peak-heating load at the start of a day and cool the boiler if the load is removed. When the load is first introduced, the boiler warms to operating temperature by circulating the flow around the back-end loop. However, this configuration has the advantage of satisfying the load during this heat-up period using the buffer vessel as a supply of hot water while the boiler warms.

Similar to the first configuration, the system is designed to ensure that the boiler return temperature does not fall below the minimum return temperature permitted by the design of the boiler. When the demand falls to zero, the buffer vessel will absorb a proportion of the heat stored within the biomass boiler. If the boiler is used the following day the hot water that has been stored within the buffer vessel can be used to contribute towards the peak load while the boiler warms. If the buffer vessel is capable of contributing towards peak load then the system pump must be rating at the peak load. Otherwise, the system pump and the boiler pump will both be rated at the boiler maximum output.

A typical buffer vessel will only hold a small volume of water so it is unlikely to be able to provide hot water for long. Consequently, the boiler must be ignited with enough time to warm before the buffer vessel is depleted. Otherwise, the hot water from the buffer vessel will deplete and the demand from the load will not be satisfied.

It is a requirement that the buffer vessel must retain a volume of cooler water throughout the day in case the boiler is shutdown unexpectedly. For this reason, a buffer vessel is unable to store hot water when a surplus is available unlike a thermal store. Therefore, the buffer vessel will only be active when it is capable of contributing towards the heating demand or during boiler shutdown. Once the buffer vessel is depleted it will be bypassed altogether (19).

3.3.2.2. Governing Equations

Figure 3.3.2.2 is a flow chart, which shows the calculation process used to model this configuration.

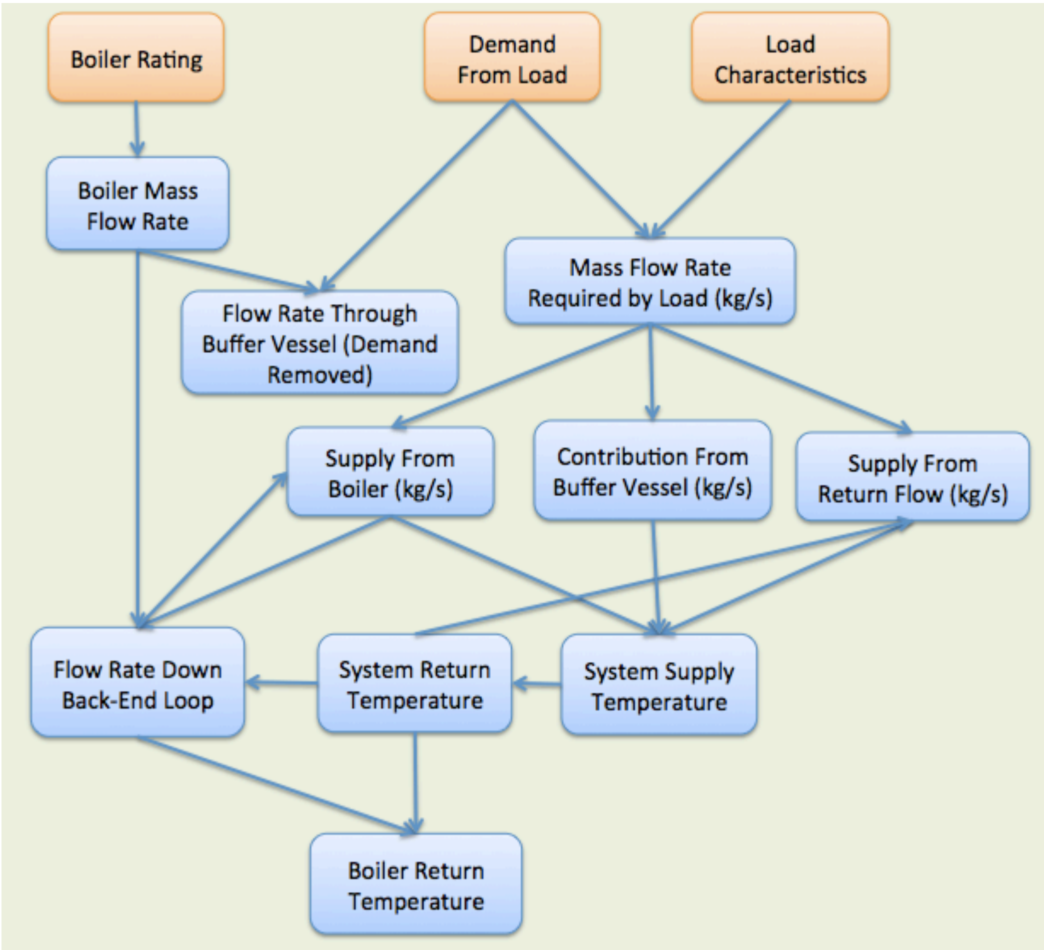


Figure 3.3.2.2: Flow Chart of Second System Calculation Process

The conditions demanded by the load from the two pipes prior to the three-port mixing valve were calculated in the same manner as with the previous configuration. Similarly, the conditions around the back-end loop of the biomass boiler were modelled using the same methods as the first configuration. The main difference when modelling this configuration comes within the middle section of the diagram due to the addition of the buffer vessel, illustrated in Figure 3.3.2.

Buffer Vessel Contribution

As with the previous configuration, the training tool first calculates the proportions of hot water demanded from the biomass boiler/buffer vessel and the proportion required from the cooler return flow. This allows the training tool to calculate the flow rate of the hot water provided to the load from the buffer vessel when the load is first introduced.

The training tool uses a conditional 'AND' statement nested within an 'IF' statement to find the buffer vessel supply conditions. The equation has three main criteria:

1) Firstly, when a load exists and the boiler is not up to flow temperature the supply from the buffer vessel is equal to the total demand of hot water required by the load.
2) Secondly, if the boiler is up to flow temperature then the buffer vessel supply will be equal to the flow rate of the hot water required by the load minus the maximum supply of hot water available from the biomass boiler taking into account the flow circulated around the back-end loop:

$$\text{BV Supply } = HotW\ Demand\ (Load)\left(\frac{kg}{s}\right) - Boiler\ Max\ Supply\ \left(\frac{kg}{s}\right) \quad \text{equation 3.3.2.2.1}$$

$$Boiler\ Max\ Supply\ (kg/s) = \frac{T_{bf} - T_{bmr}}{T_{bf} - T_{lr}}\dot{m}_b \quad \text{equation 3.3.2.2.2}$$

3) Otherwise, the supply from the buffer vessel will be zero.

However, because of the increased complexity of this configuration and the limitations of Excel iterations were needed to find the correct valves for the supply of hot water from the buffer vessel.

The capacity of hot water within the buffer vessel is dependent on the quantity of hot water that is leaving the vessel to supply the load. However, the supply from the buffer vessel is in turn dependent on the capacity of hot water that is available within the buffer vessel. That is to say, if the buffer vessel contains hot water then it will be capable of contributing towards the load if necessary. However, if the buffer vessel has been depleted then the supply (kg/s) will be equal to zero.

This is why it was necessary to include a second column of corrected values within the training tool calculation table for the supply from the buffer vessel. This second column corrects the primary values calculated for the buffer vessel supply if the buffer vessel has been depleted. The logic is as follows:

1) IF the volume of hot water held within the buffer vessel from the previous time step is smaller than the current time step AND the buffer vessel has been partially depleted then, the buffer vessel supply is equal to:

$$BV\ Supply = \dot{m}_b - \dot{m}_{\min back-end\ loop} \quad equation\ 3.3.2.2.3$$

This first condition refers to the period in which the boiler is shutting down. During this period the capacity of hot water within the buffer vessel will increase as the biomass boiler transfers heat into the volume of cool water stored within the buffer vessel. In this scenario the spreadsheet will return a negative value for the buffer vessel supply as the flow is directed down through the buffer vessel as it absorbs the heat previously stored within the biomass boiler.

2) IF the buffer vessel has no volume of hot water then its supply to the load will be equal to zero
3) Otherwise, the buffer vessel supply will be equal to the primary value previously calculated within the first column.

Once the supply of hot water stored within the buffer vessel has been depleted at the start of the day, the boiler must work alone to feed the load. In the scenario where the demand exceeds the rating of the boiler, the training tool models the flow dilution using the same equations used within the first configuration.

3.3.3. BB with Back-End Valve, Four-Port Thermal Store, Three-Port Mixing Valve

The third and final configuration includes a large 4-port thermal store instead of the buffer vessel seen in the previous biomass boiler system. The thermal store allows the boiler to be sized at a much smaller percentage of the peak-heating load than what would otherwise be possible. Other studies have found that a biomass boiler can be sized at approximately 30% of the peak-heating load depending on the demand profile shape while providing close to 100% of the annual heating demand. This configuration also allows the boiler to run near its capacity throughout the entire day increasing the efficiency of the biomass boiler system. Importantly, a proportion of the thermal store is used as a buffer vessel to cool the biomass boiler upon shutdown. Figure 3.3.3.1 below shows the typical piping configuration for a biomass boiler system of this type.

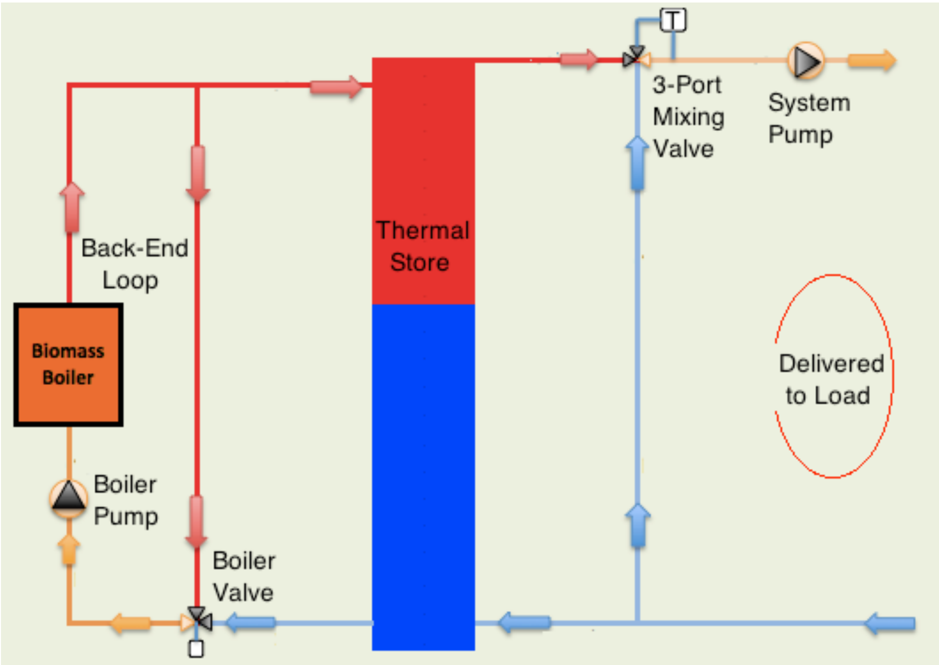


Figure 3.3.3.1: Biomass Boiler with Back-End Valve, Four-Port Thermal Store, and a Three-Port Mixing Valve

3.3.3.1. System Operation

The training tool includes two days of simulation for this configuration. During 'DAY 1' the biomass boiler is ignited from cold at the very start of the day while the thermal store is considered to be full of the cooler return water. Contrastingly, 'DAY 2' of the simulation includes the hot water stored within the thermal store from the previous night. If designed correctly a biomass boiler system of this type should be operating as in 'DAY 2' for the vast majority of the year. For this reason, the results given by 'DAY 2' of the training tool are the more relevant set of results. A summary of the system operation is as follows (19):

1) As with the other configurations, the flow circulates around the back-end loop using the boiler pump while the boiler warms.

2) Once the boiler has warmed to operating temperature it will begin to supply the thermal store with hot water. Assuming perfect stratification within the thermal store, the hot-cold water interface seen in Figure 3.3.3.1 above will begin to move down the length of the store until the lower temperature sensor is reached. If no load exists at the point then the boiler will operate in slumber mode until a load is introduced.
3) When a load is introduced, the biomass boiler will be used to match the demand from the load at first. If the demand increases above the rating of the boiler then the thermal store will start to deplete as it begins to contribute towards the heating load. At this point both the boiler pump and the system pump work to feed the load. Again, a three-port mixing valve is used to mix the flow from the biomass boiler and thermal store with the return from the load to acquire the flow conditions demanded by the load.
4) Once the load is withdrawn at the end of the day then the boiler will continue to run at its maximum output until the thermal store is at capacity. At this point boiler will operate in slumber mode until a load is reintroduced.

3.3.3.2 System Governing Equations

Due to the increased complexity of this configuration, it is best to describe the systems governing equations under each of the possible operating scenarios that the biomass boiler system is subjected to. The following section of the report will go through each of these scenarios and explain the equations that have been developed to model each. Conditional statements have been used within the Excel training tool to account for these different scenarios.

1. Boiler Heat Up

When the boiler warms up at the start of 'DAY 1' the entire flow circulates around the back-end loop while the boiler warms to operating temperature. During this period the system does not provide the load with hot water even if a demand exist. The boiler flow temperature will progress as previously discussed in section 3.2 using the linear heat-up profile developed for the training tool.

Once the boiler has reached its operating temperature the thermal store will begin to charge and hot water can be provided to the load. The same equations were used to model the flow around the back-end loop during this period as with the other biomass boiler systems.

2. Normal Operation

During normal operation the thermal store is charging and discharging while the biomass boiler system works to feed the demand from the load. However, if the demand is equal to the rating of the boiler then the capacity of the thermal store will remain unchanged.

The system is modelled to allow the biomass boiler to operate at its maximum output until the thermal store has reached its capacity. To achieve this, a constant boiler return temperature was required until the thermal store had reached its capacity. At this point the biomass boiler will fire down to meet the demand from the load alone and the boiler return temperature begins to increase. When the demand increases above the rating of the boiler the thermal store begins to deplete.

The equations used to model the flow conditions around the back-end loop are similar to those used to model the previous configurations. The equations ensure that the boiler maintains a constant return temperature while the thermal store is charging. In the training tool it is assumed that the temperature of water returned to the boiler from the thermal store is equal to the temperature of the cool water returned by the load.

The required mass flow rate through the boiler back-end loop, designed to maintain the boiler return temperature (T_{br}), is shown below in equation 3.3.3.2.1. The equation was derived using the same method shown in section 3.3.1.2.

$$y = \dot{m}_{bl} = \frac{(T_{br} - T_{lr})\dot{m}_b}{(T_{bs} - T_{lr})} \qquad equation\ 3.3.3.2.1$$

The flow down the back-end loop will only differ from this value during two scenarios.

1. During the boiler heat-up period in which the entire mass flow rate of the boiler will circulate round the back-end loop until the flow is up to operating temperature.
2. Secondly, when the thermal store has reached its capacity and the boiler operates alone to match any demand from the load.

The demand from the load determines the flow rates of both of the pipes entering the three-port mixing valve. These proportions are calculated as previously discussed in the first biomass boiler configuration and in the three-port mixing valve section of the report.

Thermal Store and Buffer Vessel Section

As previously discussed, the thermal store is modelled to include a buffer vessel at the bottom section of the store. While some manufacturers claim that their biomass boilers do not require a buffer vessel it has been assumed within the training tool that a proportion of the thermal store will always include an area for a buffer vessel. The required buffer vessel volume is calculated within the training tool using the equations shown in section 2.2 of the report.

When the demand from the load is below the rating of the boiler and the thermal store is charging the training tool is designed to ensure that a volume of cold water always remains at the bottom of the thermal store to ensure that the boiler can be cooled upon shutdown.

In practice, the quantity of energy within a thermal store is found using temperature sensors up the length of the thermal store. However, for the purpose of the training tool the quantity of hot water stored is calculated considering the flow rate into the thermal store and its volume.

In other words, the quantity of hot water within the thermal store is calculated by considering the surplus flow available from the boiler (excluding the proportion of the flow diverted down the back end loop and the proportion that feeds the demand from the load) and the length of time the surplus is available. Any surplus hot water that is left over is pumped down into the thermal store pushing the hot water interface down towards the bottom of the thermal store. The day is split into five-minute time intervals and the flow of hot water is messaged in kg/s. Therefore, the quantity of hot water within the store is calculated as the number of seconds in each time interval (300 seconds) multiplied by the surplus flow available.

For example, after a five-minute interval with a surplus flow of 1kg/s the thermal store will replace 300 litres ($300\ secs \times 1kg/s$) of the colder water at the bottom of the thermal store with the hot water from the biomass boiler. Similarly, when the demand from the load is higher than the rating of the boiler, the training tool will return a negative surplus and the hot water within the thermal store will begin to deplete.

The total volume of hot water within the thermal store at any given point is equal to the quantity of hot water available from the previous time interval plus the quantity of hot water pumped into the store during the current five-minute time interval.

A conditional statement is used within the training tool to ensure that the volume of hot water within the thermal store does not exceed its volume. It also ensures that the volume of hot water does not return a negative value within the table of results. This is illustrated in equation 3.3.3.2.2:

$$TS\ HotW\ Vol = (Surplus\ Flow \times 300\ secs) +\ Vol\ (Previous\ Time\ Step) \quad equation\ 3.3.3.2.2$$

The logic used to calculate the volume of hot water within the thermal store is as follows:

1) IF the volume of hot water calculated is below zero then the volume of hot water is equal to zero. This scenario is relevant when the thermal store is fully depleted. If the store becomes empty this ensures that the volume of hot water does not become negative.
2) IF the volume of hot water returned by equation 3.3.3.2.2 is smaller than the volume of the thermal store then the quantity of hot water is equal to the volume calculated.
3) Otherwise, the thermal store is full and the volume of hot water will be equal to the thermal store volume minus the buffer vessel volume. The conditional statement used ensures that a volume of cooler water remains at the bottom of the store as a buffer vessel in case the boiler is unexpectedly shut down.

3. Thermal Store Depleted

When the thermal store has been depleted, the biomass boiler works alone to satisfy the demand from the load. However, it is possible that demand will exceed the rating of the biomass boiler while the thermal store is depleted. In this scenario the temperature of the flow from the thermal store to the load will fall and so will the load supply temperature. This is similar to the flow dilution seen previously in section 3.3.1.1 of this report.

The temperature of the flow from the thermal store is calculated depending on the status of the store:

1) If the store has a supply of hot water available then the temperature of the water from the top of the store will be at the boiler flow temperature.
2) If the thermal store has been depleted and the demand is above the rating of the boiler then the temperature of the water provided to the load will be a combination of the hot water directly from the boiler and that of the cooler water within the store.

When the thermal store has been depleted and the demand exceeds the rating of the boiler the temperature of the flow exiting the thermal store will begin to fall.

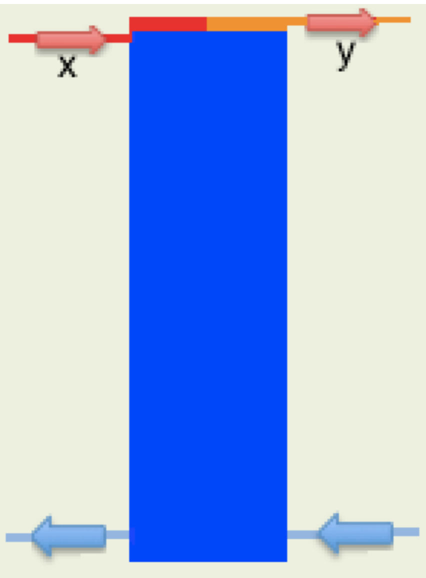


Figure 3.3.3.2

Equation 3.3.3.2.3, shown below, was used to model this and calculate the temperature of the flow from the thermal store when the store has been depleted.

$$T_{TS} = \frac{T_{bs}x + (y - x)T_{lr}}{y} \qquad \textit{equation } 3.3.3.2.3$$

In Equation 3.3.3.2.3, 'x' represents the flow rate into the thermal store from the boiler (kg/s) and 'y' is the total flow rate demanded from the thermal store by the load. This is illustrated in Figure 3.3.3.2. Again, this equation is nested within a conditional statement within the training tool so that it is only used under the correct circumstances.

The temperature of the water provided to the load is then a combination of the flow temperature from the thermal store mixed with the cooler return water using the three-port mixing valve. The training tool uses the same method shown in section 3.3.1.1 of this report to model flow dilution in the load supply and return temperatures as the demand exceeds the capabilities of this biomass boiler system.

4. Thermal Store Full To Capacity

When the thermal store is at capacity the boiler will fire down to match the demand from the load only, which influences the boiler return temperature. The main difference within the training tool during this scenario is the calculation process for the back-end loop flow rate. Two columns are used within the training tool to calculate the flow rate down the back-end loop. This is because the back-end loop flow rate is dependent on the conditions within the thermal store, but the capacity of the thermal store is partially dependent on the back-end loop flow rate. Consequently, two columns were used to avoid complicated iterations within the training tool.

When the thermal store is at capacity and the demand is below the rating of the boiler the flow rate round the back-end loop is equal to:

$$\dot{m}_{bel} = \dot{m}_b - \dot{m}_{tsr} \qquad equation\ 3.3.3.2.4$$

Where $\dot{m}_b$ is the boiler flow rate and $\dot{m}_{tsr}$ is the flow rate of the cool water returned towards the boiler from the thermal store. However, outwith these circumstance the back-end loop flow rate calculated using equation 3.3.3.2.1 in the first (uncorrected) column of results.

Table 3.3.3.2 below illustrates how the flow around the back end loop changes under different demand scenarios.

Table 3.3.3.2: Illustration of Calculation Procedure

Back-End Loop (kg/s)	Back Loop crt (kg/s)	Flow into TS (kg/s)	Return from TS (kg/s)	Surplus Flow (kg/s)	TS charge (litres)	TS charge (%)	Boiler Tf (°C)
2.38	2.38	0.00	0.00	0.00	0.00	0.00%	10.0
2.38	2.38	0.00	0.00	0.00	0.00	0.00%	18.9
2.38	2.38	0.00	0.00	0.00	0.00	0.00%	27.9
2.38	2.38	0.00	0.00	0.00	0.00	0.00%	36.8
2.38	2.38	0.00	0.00	0.00	0.00	0.00%	45.7
2.38	2.38	0.00	0.00	0.00	0.00	0.00%	54.6
2.38	2.38	0.00	0.00	0.00	0.00	0.00%	63.6
2.38	2.38	0.00	0.00	0.00	0.00	0.00%	72.5
2.38	2.38	0.00	0.00	0.00	0.00	0.00%	81.4
1.73	1.73	0.65	0.65	0.18	53.25	1.33%	85.0
1.73	1.73	0.65	0.65	0.18	106.49	2.67%	85.0
1.73	1.73	0.65	0.65	0.18	159.74	4.00%	85.0
1.73	1.73	0.65	0.65	0.18	3940.26	98.69%	85.0
1.73	1.91	0.47	0.65	0.18	3992.47	100.00%	85.0
1.73	1.91	0.47	0.65	0.18	3992.47	100.00%	85.0
1.73	1.88	0.50	0.65	0.15	3992.47	100.00%	85.0
1.73	1.85	0.53	0.65	0.12	3992.47	100.00%	85.0
1.73	1.82	0.56	0.65	0.09	3992.47	100.00%	85.0
1.73	1.80	0.59	0.65	0.06	3992.47	100.00%	85.0
1.73	1.77	0.61	0.65	0.03	3992.47	100.00%	85.0
1.73	1.74	0.64	0.65	0.01	3992.47	100.00%	85.0
1.73	1.73	0.65	0.65	-0.02	3985.87	99.83%	85.0
1.73	1.73	0.65	0.65	-0.15	118.77	2.97%	85.0
1.73	1.73	0.65	0.65	-0.15	73.31	1.84%	85.0
1.73	1.73	0.65	0.65	-0.15	27.86	0.70%	85.0
1.73	1.73	0.65	0.65	-0.15	0.00	0.00%	85.0
1.73	1.73	0.65	0.65	-0.15	0.00	0.00%	85.0
1.73	1.73	0.65	0.65	-0.15	0.00	0.00%	85.0
1.73	1.73	0.65	0.65	-0.15	0.00	0.00%	85.0
1.73	1.73	0.65	0.65	-0.15	0.00	0.00%	85.0

Table 3.3.3.2 is spilt up into three sections to illustrate the different scenarios that influence the value of the flow rate round the back-end loop. It also shows the two columns used to calculate this value for each time step. The three sections of the table refer to the following scenarios:

1) During the heat-up period the flow rate round the back-end loop is equal to the boiler flow rate.
2) When the thermal store has been filled to capacity (100%) the second back-end loop column corrects the values calculated in the first column.
3) Finally, when the thermal store has been fully depleted (0%) back-end loop flow rate is equal to the maximum value possible which maintains the minimum boiler return temperature, in this case 1.73kg/s.

3.3.4. Auxiliary Gas Boiler Addition

As previously discussed, many biomass boiler systems include one or more auxiliary boilers to satisfy the load when the demand exceeds the rating of the biomass boiler. For this reason, the training tool includes two auxiliary boiler options as an add-on to the original three main biomass boiler configurations. The two configurations differ in the manner in which the auxiliary boilers are connected. Both options are detailed in the following section of the report.

3.3.4.1. Auxiliary Gas Boiler Connected Prior to Load

The first auxiliary boiler including in the training tool is connected to the biomass boiler system after the 3-port mixing valve and prior to the heating load. This is illustrated in Figure 3.3.4.1 below. In this example the load has a demand of 500kW. The biomass boiler provides the load with the first 350kW and the auxiliary boiler works to provide the additional 150kW.

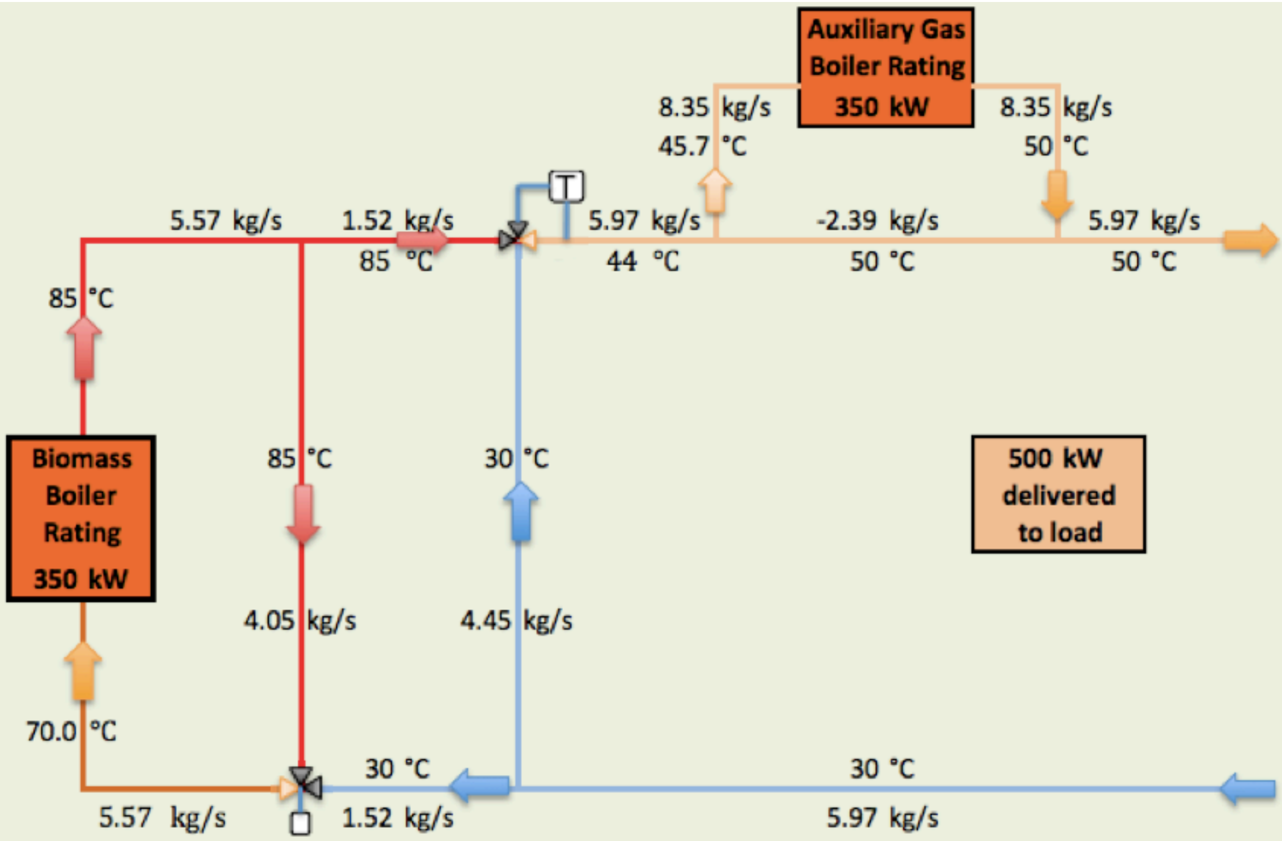


Figure 3.3.4.1: Example of Biomass Boiler with Auxiliary Boiler 1

When the demand from the load increases above the rating of the biomass boiler, the auxiliary boiler will begin to contribute towards the demand for hot water. In this piping arrangement, the auxiliary boiler works to re-heat the flow that has been diluted below the required temperature demanded by the load using the return flow. The auxiliary boiler re-heats the flow up to the temperature demanded by the load, in this case 50°C.

However, it soon becomes clear that there are limitations to the design of this configuration. With this particular design the auxiliary boiler must be above a certain rating. This is because the flow rate to the load is provided directly through the auxiliary boiler. For this reason the mass flow rate of the auxiliary boiler must be at least as large as the maximum mass flow rate required by the load. Consequently, if the demand from the load is 400kW with a 20°C temperature drop and the auxiliary boiler is 50kW with a 10°C temperature drop, then the auxiliary boiler will only be able to handle a mass flow rate of 1.19kg/s despite the load requiring a mass flow rate of 4.77kg/s. This leads onto the next auxiliary boiler configuration, which is designed to allow an auxiliary boiler of a much smaller size to be included into the biomass boiler system.

With this configuration, it has been assumed in the training tool that the auxiliary boiler rating is equal to the peak-heating load minus the rating of the biomass boiler. For this reason the boiler system will always be capable of providing the demand from the load and consequently there will never be an occasion where dilution of the flow to the load occurs as discussed previously in the piping configurations without an auxiliary boiler. In the case where the auxiliary boiler is too small to handle the mass flow rate required by the load, a 'warning' message comes up within the training tool to alert the user that alterations must be made.

3.3.4.2. Auxiliary Gas Boiler Connected In between two 3-Port Mixing Valves.

This next method of connecting an auxiliary boiler to a biomass boiler system allows an auxiliary boiler with a much smaller rating to be connected. This is achieved using an additional 3-port mixing valve. This is illustrated in the diagram below. Again, in this example a demand of 500kW is satisfied at first using 350kW from the biomass boiler and then with an additional 150kW from the auxiliary boiler.

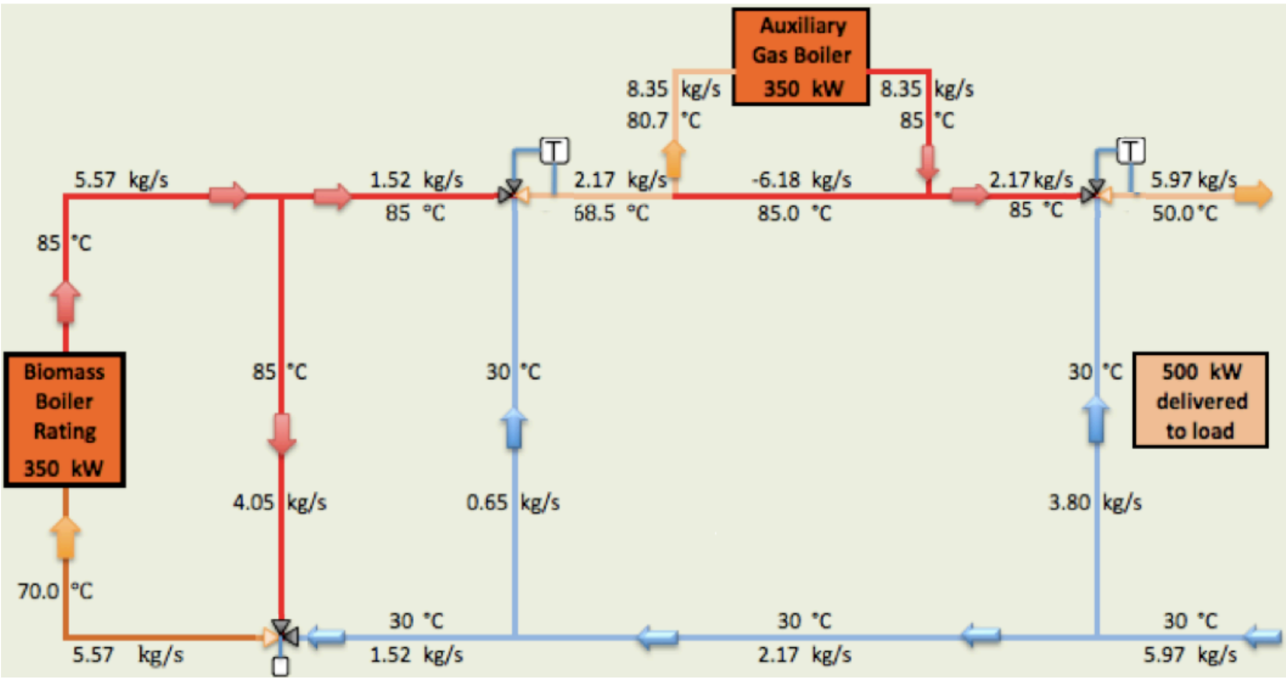


Figure 3.3.4.2: Example of Biomass Boiler with Auxiliary Boiler 2

By recycling the return flow from the load twice using an additional 3-port mixing valve, the auxiliary gas boiler must only be large enough to handle the flow rate of the hotter water demanded by the load (i.e. the 2.17kg/s of 85°C water prior to the second 3-port mixing valve seen in Figure 3.3.4.2). Consequently, with a demand of 500kW the auxiliary boiler can be as small as approximately 91kW assuming a 10°C boiler temperature drop instead of the 250kW required by the previous configuration.

Again it is assumed that the rating of the auxiliary boiler is equal to the peak-heating load minus the rating of the biomass boiler and so no flow dilution of the flow out to the load will occur.

The temperatures and flow rates throughout the piping configuration are calculated from the far right hand side and far left hand side of the configuration first to then find the conditions through the middle of the system. Knowing the auxiliary boiler design flow temperature and the temperatures demanded and returned by the load, the mass flow rate required by the load can be found. From this the flow rates from the auxiliary boiler towards the second 3-port mixing valve and that recycled by the load can be found using the same method detail in section 3.3.1.2. of this report.

Similarly, the minimum flow rate through the back end loop of the biomass boiler and consequently the supply of water provided by the boiler through the top of the piping configuration is calculated as previously discussed. From these values at either end of the system, and keeping in mind that the flow through each section of the system must be balanced, the conditions through the middle of the system and through the auxiliary boiler can be found. The flow of return water entering the left hand 3-port mixing valve is found my subtracting the flow rate of hot water supplied to the load (from the biomass boiler) from the flow rate of the return water remaining after the flow diverted towards the right hand 3-port mixing valve. Figure 3.3.4.3 below, is used to illustrate how the conditions through the auxiliary boiler are found.

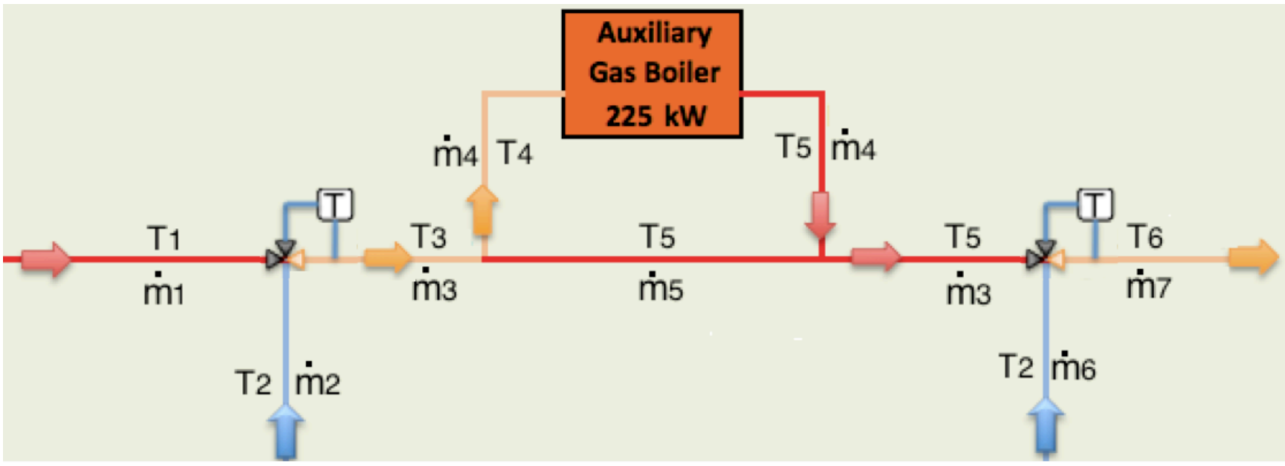


Figure 3.3.4.3: Explanation of Auxiliary Boiler 2

And so, with the conditions at either end of the biomass boiler already known the values down the middle section of the diagram above can be found as follows, where the terms in the equations refer to those seen in Figure 3.3.4.3

$$\dot{m}_3 = \dot{m}_1 + \dot{m}_2 \qquad equation\ 3.3.4.2.1$$

and

$$T_3 = \frac{(T_1 \times \dot{m}_1) + (T_2 \times \dot{m}_2)}{(\dot{m}_1 + \dot{m}_2)} \qquad equation\ 3.3.4.2.2$$

And so, the mass flow rates and temperatures around the auxiliary boiler loop can be calculated using the following equations.

$$\dot{m}_4 = \frac{Aux.Boiler\ Rating\ (kW)}{\Delta T_{axb} \times C_p} \qquad equation\ 3.3.4.2.3$$

.

$$m_5 = \dot{m}_4 - \dot{m}_3 \qquad equation\ 3.3.4.2.4$$

$$T_4 = \frac{(T_3 \times \dot{m}_3) + (T_5 \times \dot{m}_5)}{(\dot{m}_3 + \dot{m}_5)} \qquad equation\ 3.3.4.2.5$$

During the scenario where the demand on the auxiliary boiler is zero, the flow avoids the gas boiler all together and T_3 becomes equal to T_5 and $\dot{m}_3$ becomes equal to $\dot{m}_5$. Additionally, the flow $\dot{m}_2$ becomes zero, as there is no longer a need for two 3-port mixing valves.

4. Training Tool Overview

This section of the report will go through the details of the training tool when being used by an operator. This includes the user inputs required by the training tool to accurately model each configuration, the demand profiles created using the biomass boiler sizing tool, the user interface, and the dynamic diagrams created to demonstrate the operation of each of the configurations.

4.1. User Inputs

Each of the biomass boiler configurations that are included into the training tool require a number of inputs which the user can alter to select the most appropriate design for a specific demand profile. This allows a user to find the optimum biomass boiler system design for a specific heating load by assessing the results after alterations are made to the variables.

The first key variable used by the spreadsheet is the demand profile. The tool provides four typical 24-hour demand profiles for different building types for a design winter day. These demand profiles were created using the Biomass Boiler Sizing Tool. The spreadsheet also provides the option for the user to upload an external demand profile into the training tool.

A pull down menu is available to select the desired demand profile. The training tool is capable of automatically updating the table of results to include the new demand profile by selecting the appropriate number (1-5) from the pull down menu. Figure 4.1.1 shows how the demand profiles are selected in the training tool for each configuration. The demand profile seen in figure 4.1.1 also indicates the rating of the boiler in comparison with the demand profile of the load. The ratings of any auxiliary boilers are also shown graphically on the demand profiles.

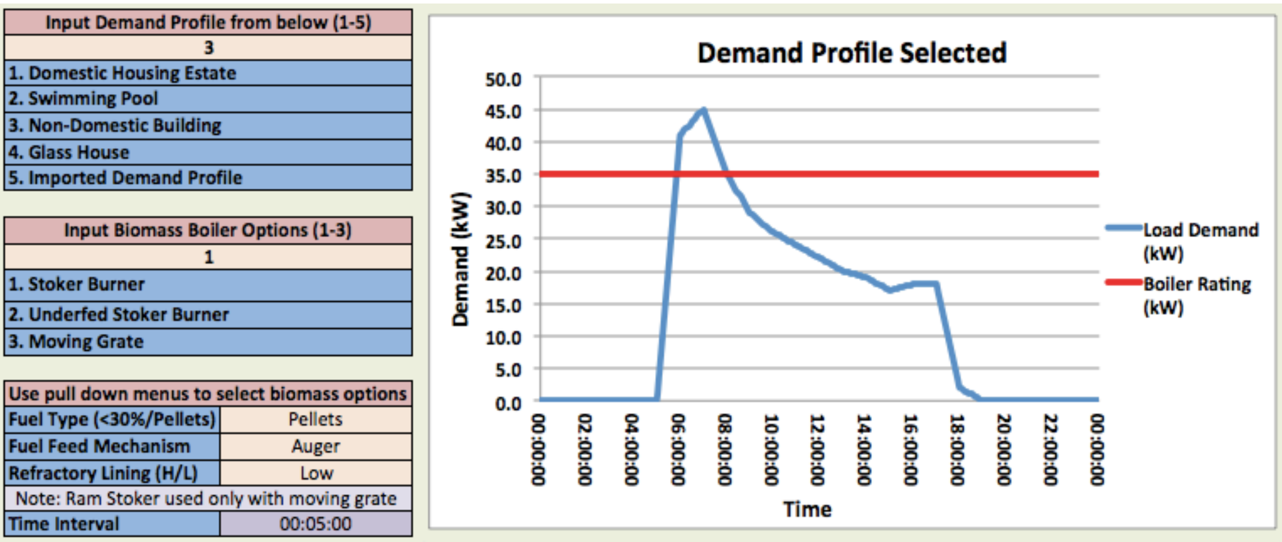


Figure 4.1.1: Diagram of Training Tool Demand Profile Selection

The demand profiles that were created and included in the training tool included the following building types:

- Glass house
- Swimming Pool
- Non-Domestic Building
- Domestic Housing Estate

The training tool allows any of these demand profiles to be selected for each of the configurations. The demand profiles are shown graphically below in figure 4.1.2. It can be observed that the shape of each profile can differ greatly. This can have a large impact on the type of biomass boiler system that is suitable for a given demand profile and the performance of any additional components such as a thermal store. This will be demonstrated later in the report using the case studies examined using the training tool. The characteristics of the demand profiles not included in the case study are listed in the appendix of this report.

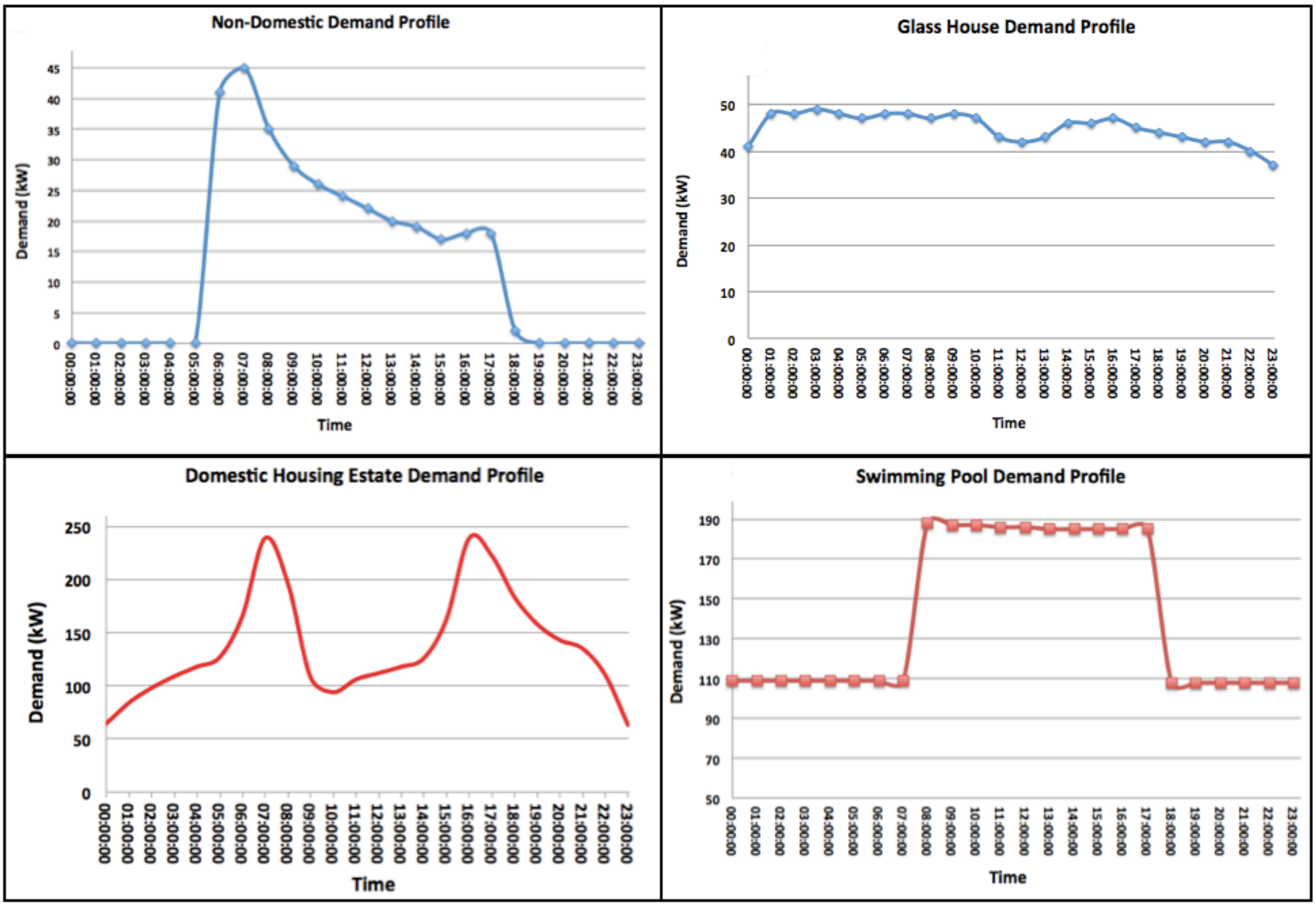


Figure 4.1.2: Diagram of the Training Tool Four Demand Profiles

Boiler Characteristics Options

The training tool also allows the user to alter the boiler characteristics. These characteristics can effect to size of the buffer vessel required by the system (previously discussed in section 2.2 of this report) and the heat-up and cool-down periods. The variables also allow the user to accurately design the desired biomass boiler system. The biomass boiler options that are built into the tool include:

Boiler Type:

- Stoker Burner
- Underfed Stoker
- Moving Grate

Thickness of Thermal Lining:

- High
- Low

Boiler Feeding Mechanism:

- Auger
- Ram Stoker

Again, each of the options can be selected using a drop down menu within the training tool. The variables that are available to the user of the tool are used to size the buffer vessels and complete the calculations in the main result tables of each configuration. Other variables are included into the tool to achieve an accurate representation of the desired biomass boiler system. These include:

- Thermal store volume (litres)
- Biomass and Auxiliary Boiler Rating (kW)
- Temperature of flow from boiler ($°C$)
- Minimum return temperature to boiler ($°C$)
- Temperature of water demanded by load ($°C$)
- Temperature of return from load ($°C$)

The system variables described above can be chosen using the values given by the Biomass Boiler Sizing Tool, allowing the tool to be used as a valuable addition to the sizing tool developed by the Carbon Trust. Alternatively, the variables can be altered to find the optimal biomass boiler system design. Changes in the variables can be quickly assessed using the system feedback, which displays the performance of the selected systems in satisfying the heating load.

4.2. User Interface

The training tool is designed to be as user friendly as possible to allow the tool to be easily used. The variables that can be altered by the user include drop-down menus to allow the user to select the appropriate inputs. Figure 4.2.1 below shows the area dedicated within the training tool for the user inputs. The boxes shaded in yellow below are available for the user to alter, while the purple boxes are calculated using the inputs and options selected.

Variables below can be altered and the results shown in the tables will update automatically

Boiler Variables	
Boiler Rating (kW)	100
Specific Capacity (J/kg)	4190
Turn-Down Ratio	0.40
Boiler Min (kW)	40.00
Volume Ratio	8
Volume (litres)	800
Time to heat up (hrs)	00:41:54

Temperature Variables	
Boiler Supply Temp (°C)	85
Boiler Min Tr (°C)	70
Demand Temp (°C)	50
System Return Temp (°C)	30
Min Water Temp (°C)	10

Pumping Information	
Boiler Pump (litres/sec)	4.91
System Pump (litres/sec)	4.91

Time Interval	00:05:00
Min Back-End Loop (kg/s)	1.16

Input Demand Profile from below (1-5)
1
1. Domestic Housing Estate
2. Swimming Pool
3. Non-Domestic Building
4. Glass House
5. Inported Demand Profile

Input Biomass Boiler Options (1-3)
3
1. Stoker Burner
2. Underfed Stoker Burner
3. Moving Grate

Use pull down menus to select biomass options	
Fuel Type (<30% or Pellets)	Pellets
Fuel Feed Mechanism	Auger
Refractory Lining (H/L)	High
Note: Ram Stoker used only with moving grate	

Buffer Vessel Data	
Buffer Vessel Size (l/kW)	8.33
Buffer Vessel Volume (litres)	833

Figure 4.2.1: Diagram of Training Tool User Interface

Additionally, each configuration includes two columns at the end of each table of results, which provide information on the performance of each configuration under a specific scenario. The first of these columns is labelled 'Load Satisfied'. For each five-minute time step the column will confirm if the load has been satisfied with 'YES' highlighted in green, or 'NO' in red if the biomass boiler system is inadequate. Similarly, if the load is not satisfied because the auxiliary boiler is incorrectly sized for the particular configuration the warning message appears 'NO-Aux boiler too small'. The second set of performance columns that are included into the training tool allow the user to assess the status of the boilers during any period of the day. Labelled 'Boiler Status' the columns inform the user whether the boiler is ON, OFF, HEATING UP, or COOLING DOWN. This is illustrated in Figure 4.2.2 below.

B.Boiler Status	Aux.Boiler Status	Load Satisfied?
OFF	OFF	NA
OFF	OFF	NA
OFF	OFF	NA
OFF	OFF	NA
OFF	OFF	NA
OFF	OFF	NA
OFF	OFF	NA
OFF	OFF	NA
WARM-UP	OFF	NO
WARM-UP	OFF	NO
WARM-UP	OFF	NO
WARM-UP	OFF	NO
WARM-UP	OFF	NO
WARM-UP	OFF	NO
WARM-UP	OFF	NO
WARM-UP	OFF	NO
ON	OFF	YES
ON	OFF	YES
ON	OFF	YES
ON	OFF	YES
ON	OFF	YES

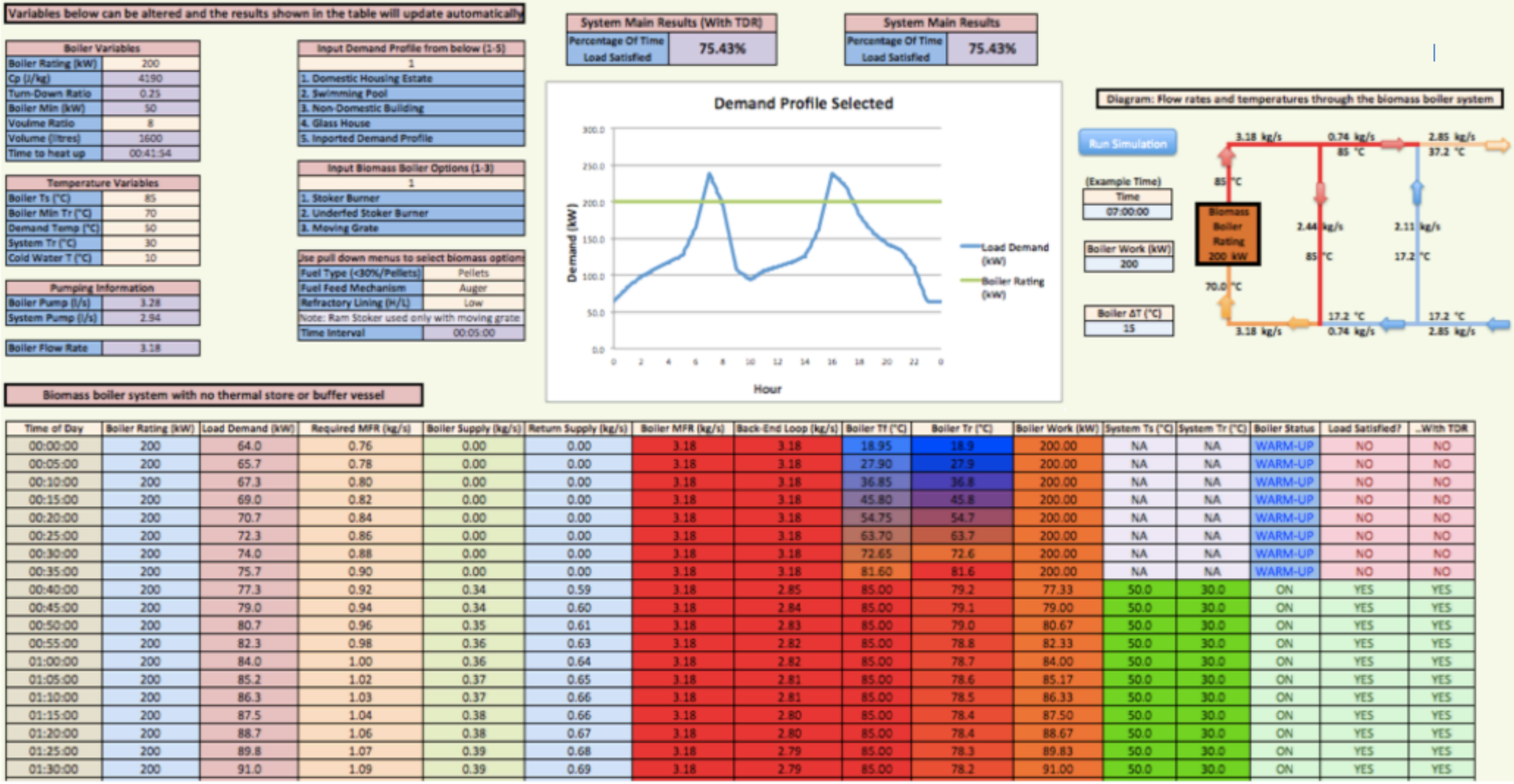
Figure 4.2.2: Diagram of Training Tool Boiler System Feed-Back

Figure 4.2.4 on the following page is a screen shot of the entire user interface for the first and most basic biomass boiler configuration. The main user inputs are on the left hand side. This is where the user can select the boiler characteristics and the desired demand profile. Once the required inputs are selected, the demand profile is updated automatically both within the table of calculations and in the graph seen in the middle of the diagram. Finally, on the far right hand side of the diagram the dynamic diagram can be seen which allows the user to visualise the performance of the particular biomass boiler system. By clicking 'Run Simulation' the training tool will run through the entire day of results while updating the values seen across the diagram. Finally, the training tool includes a summary of the calculated results, which allows the user to quickly assess the effectiveness of the designed biomass boiler system. It gives a percentage of the design winter day in which the biomass boiler system satisfies the demand from the load. To take into consideration the turndown ratio of the biomass boilers, the tool provides a second summary of the results, which takes into consideration the turndown ratio of the boiler that is being modelled. This is achieved by including the times in which is the demand is lower than the minimum boiler output as a period where the load is not satisfied (excluding configurations which include auxiliary boilers). This returns a lower, but perhaps more accurate approximation of the performance of the biomass boiler system. This is illustrated in figure 4.2.3 below.

System Main Results	
Percentage of Day Load is Satisfied	100.00%

System Main Results (With TDR)	
Percentage of Day Load is Satisfied	77.16%

Figure 4.2.3: Example of Training Tool Main Results



Time of Day	Boiler Rating (kW)	Load Demand (kW)	Required MFR (kg/s)	Boiler Supply (kg/s)	Return Supply (kg/s)	Boiler MFR (kg/s)	Back-End Loop (kg/s)	Boiler Tf (°C)	Boiler Tr (°C)	Boiler Work (kW)	System Ts (°C)	System Tr (°C)	Boiler Status	Load Satisfied?	...With TDR
00:00:00	200	64.0	0.76	0.00	0.00	3.18	3.18	18.95	18.9	200.00	NA	NA	WARM-UP	NO	NO
00:05:00	200	65.7	0.78	0.00	0.00	3.18	3.18	27.90	27.9	200.00	NA	NA	WARM-UP	NO	NO
00:10:00	200	67.3	0.80	0.00	0.00	3.18	3.18	36.85	36.8	200.00	NA	NA	WARM-UP	NO	NO
00:15:00	200	69.0	0.82	0.00	0.00	3.18	3.18	45.80	45.8	200.00	NA	NA	WARM-UP	NO	NO
00:20:00	200	70.7	0.84	0.00	0.00	3.18	3.18	54.75	54.7	200.00	NA	NA	WARM-UP	NO	NO
00:25:00	200	72.3	0.86	0.00	0.00	3.18	3.18	63.70	63.7	200.00	NA	NA	WARM-UP	NO	NO
00:30:00	200	74.0	0.88	0.00	0.00	3.18	3.18	72.65	72.6	200.00	NA	NA	WARM-UP	NO	NO
00:35:00	200	75.7	0.90	0.00	0.00	3.18	3.18	81.60	81.6	200.00	NA	NA	WARM-UP	NO	NO
00:40:00	200	77.3	0.92	0.34	0.59	3.18	2.85	85.00	79.2	77.33	50.0	30.0	ON	YES	YES
00:45:00	200	79.0	0.94	0.34	0.60	3.18	2.84	85.00	79.1	79.00	50.0	30.0	ON	YES	YES
00:50:00	200	80.7	0.96	0.35	0.61	3.18	2.83	85.00	79.0	80.67	50.0	30.0	ON	YES	YES
00:55:00	200	82.3	0.98	0.36	0.63	3.18	2.82	85.00	78.8	82.33	50.0	30.0	ON	YES	YES
01:00:00	200	84.0	1.00	0.36	0.64	3.18	2.82	85.00	78.7	84.00	50.0	30.0	ON	YES	YES
01:05:00	200	85.2	1.02	0.37	0.65	3.18	2.81	85.00	78.6	85.17	50.0	30.0	ON	YES	YES
01:10:00	200	86.3	1.03	0.37	0.66	3.18	2.81	85.00	78.5	86.33	50.0	30.0	ON	YES	YES
01:15:00	200	87.5	1.04	0.38	0.66	3.18	2.80	85.00	78.4	87.50	50.0	30.0	ON	YES	YES
01:20:00	200	88.7	1.06	0.38	0.67	3.18	2.80	85.00	78.4	88.67	50.0	30.0	ON	YES	YES
01:25:00	200	89.8	1.07	0.39	0.68	3.18	2.79	85.00	78.3	89.83	50.0	30.0	ON	YES	YES
01:30:00	200	91.0	1.09	0.39	0.69	3.18	2.79	85.00	78.2	91.00	50.0	30.0	ON	YES	YES

Figure 4.2.4: Diagram of Training Tool Entire User Interface

4.3. Training Tool Dynamic Diagrams

Each of the configurations included in the training tool is investigated within its own tab of the Excel spreadsheet. Additionally, a dynamic diagram of the specific biomass boiler system is included into each tab. The diagrams show the temperatures and flow rates on the diagram, including the level of the hot-cold water interface within any thermal store of buffer vessel.

The diagrams illustrate the performance of the biomass boiler system to the user of the training tool during a design winter day. The spreadsheet includes the button 'Run Simulation'. When this button is pressed the diagram runs a macro designed to run a faster than real time simulation of the system over a 24 hour period. The day is split up into 5-minute time intervals and the simulation runs at a speed of 1 second for every 5-minute interval. A screen shot of one of the diagrams used to run these simulations is seen below in Figure 4.3.1.

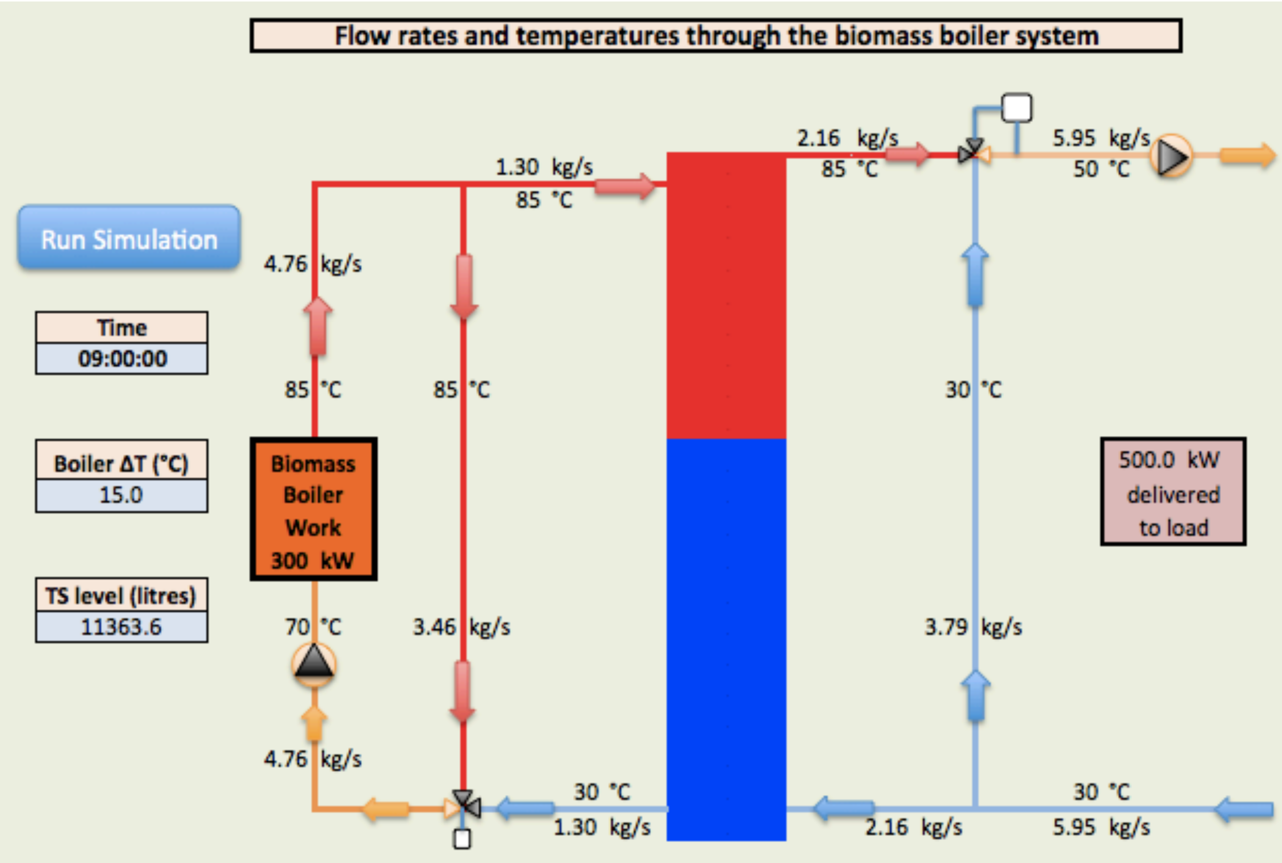


Figure 4.3.1: Example of Training Tool Dynamic Diagrams

Because the day is split into five-minute intervals there are many intervals for each daylong simulation. Recording a macro to run through the results for each time interval by hand proved to be impractical and time costly. Consequently, a loop was written within the macro for each diagram to run through the entire day automatically, removing the need to record the results for each time interval by hand. A simple example of this coding is shown in the appendix for this report.

Thermal Store Dynamic Modelling

As the simulation runs through the course of the day, the boundary between the red and blue border seen in figure 4.3.1 moves up and down the length of the thermal store. When a surplus of hot water is available from the boiler the area shaded red will move down the length of the thermal store. Similarly, when the demand increases above the rating the area shaded in blue moves upwards as the hot water within the thermal store depletes.

Conditional formatting was used to model the simulation of the thermal store. Within each cell of the thermal store an IF statement is used to calculate the temperature of the water within each section of the store. This IF statement used is shown below in equation 4.3.1.

$$= IF\left(TScharge > \left(\frac{TS\ volume}{no.sections} \times section\ no.\right), T_h, T_r\right) \qquad equation\ 4.3.1$$

The simulation is more accurate when the thermal store is modelled with a higher number of rows. If the volume of hot water within the thermal store is known the position of the red-blue barrier can be found by dividing the thermal store into several sections. Equation 4.3.1 was within each cell of the thermal store diagrams. The equation is altered to account for the cell (or section number) of the thermal store that is being calculated.

When the volume of hot water within the thermal store (calculated in the table of results) is above the volume of the particular thermal store cell then the cell will return the temperature of the hot water (T_h). Otherwise, the cell will be given the value of the colder water (T_r). When the value within the cell of the thermal store is at the boiler flow temperature the cell will be shaded in red and blue when at the temperature of the return flow.

A macro was recorded within the Excel spreadsheet to allow the ‘TScharge’ value seen in the ‘IF’ statement above for each five-minute time step of the entire 24-hour period. The macro is attached to a ‘Run Simulation’ button to begin the simulation.

5. Training Tool Case Studies

This section of the report includes two case studies designed to illustrate the operation of the training tool using demand profiles developed within the Biomass Boiler Sizing Tool. The purpose of these case studies is to analyse the usefulness of the tool as a training aid or design aid for those looking to size a biomass boiler system. The training tool is used alongside data generated by the Biomass Boiler Sizing Tool and annual load duration curves created using the RETscreen method in an attempt to find an optimum biomass boiler design for each demand profile (20).

The demand profiles were created for several building types before being imported into the training tool. However, the training tool is only capable of analysing the performance of a selected biomass boiler system for one demand profile at a time, in this case for a design winter day. To combat this annual load duration curves have been generated to ensure that the biomass boiler system that is chosen is appropriate throughout the entire year and not only during the design winter day.

5.0.1. Annual Load Duration Curves

An annual load duration curve can be used to check the suitability of a biomass boiler system throughout the course of the year. Annual load duration curves are described as a yearlong cumulative frequency distribution of the load, which takes into account the heating load throughout the course of a year. An example of annual load duration curve is seen in figure 5.0.1 below. The red line indicates the rating of the boiler, while the blue line shows the boiler turndown ratio. In this case the biomass boiler has a turndown ratio of 2:1.

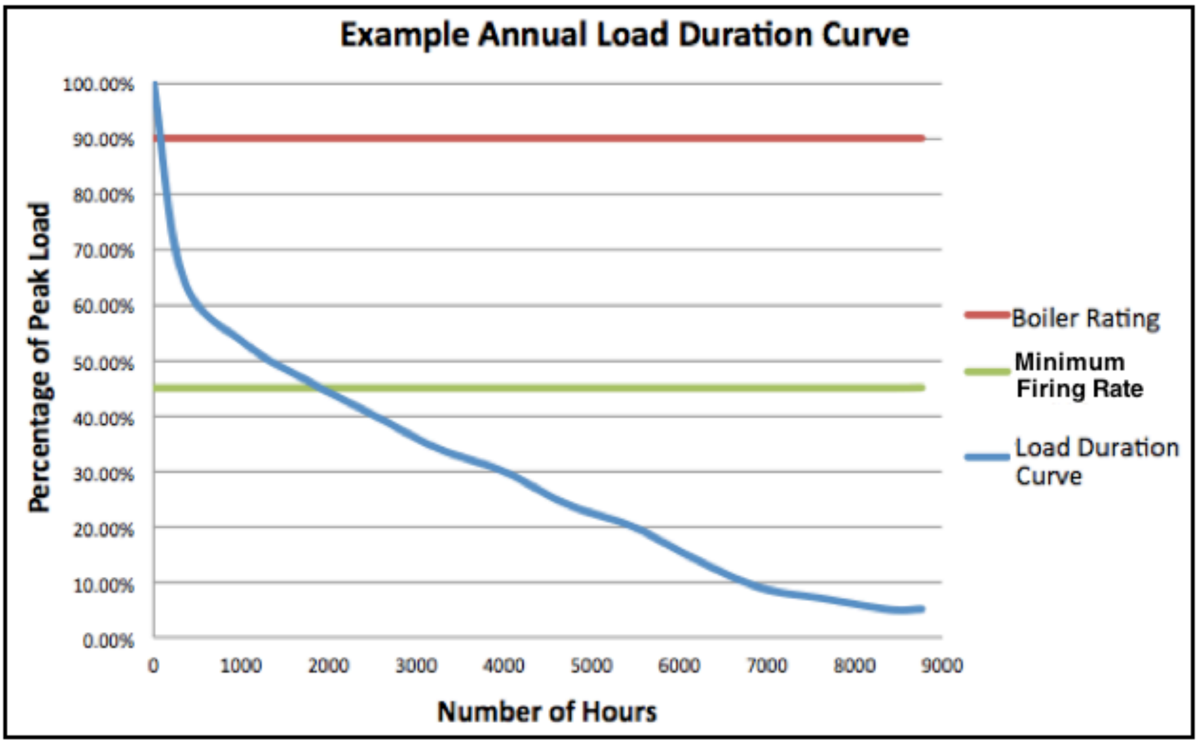


Figure 5.0.1: Example Annual Load Duration Curve

The curve is used to estimate the number of hours throughout a year in which the biomass boiler is able to satisfy the load. The area between the two lines shows the time in which the boiler is capable of matching the load. It is said that a biomass boiler system should operate between these two lines for more than 5000 hours of the year (19).

While a large biomass boiler may be capable of satisfying the peak load, it may be inefficient in providing heating for a large percentage of the year due to the poor turndown ratios associated with biomass boilers. This is demonstrated in figure 5.0.1 in which the biomass boiler is only capable of satisfying the load for 2000 hours of the year but unable to meet the demand for the remaining 6760 hours. When the heating demand is below the minimum output of a biomass boiler, it is not the case that the boiler cannot meet the low loads at all, just that it can only do so by cycling on and off, which is inefficient.

It is important to note that the training tool is not capable of creating its own annual load duration curves. The tool is only capable of analysing the performance of a biomass boiler system over a 24-hour period for one demand profile at a time. However, an annual load duration curves has been created using the RETScreen Method to illustrate how a biomass boiler system would be sized. This method has been developed by "*RETScreen® International: Clean Energy Decision Support Centre*" for biomass heating projects (20).

To create an annual load duration curve average daily outdoor temperatures are required for the location of the heating load. From this monthly degree-days can be estimated and used to derive the load duration curves. Climate data for a design year in Lerwick has been used for the purpose of this project to derive the required annual load duration curves to use alongside the training tool. For further information the full method can be found within the RETScreen user manual at www.retscreen.net/download.php/ang/126/1/Course_bioh.ppt

5.1. Case Study 1: Glasshouse

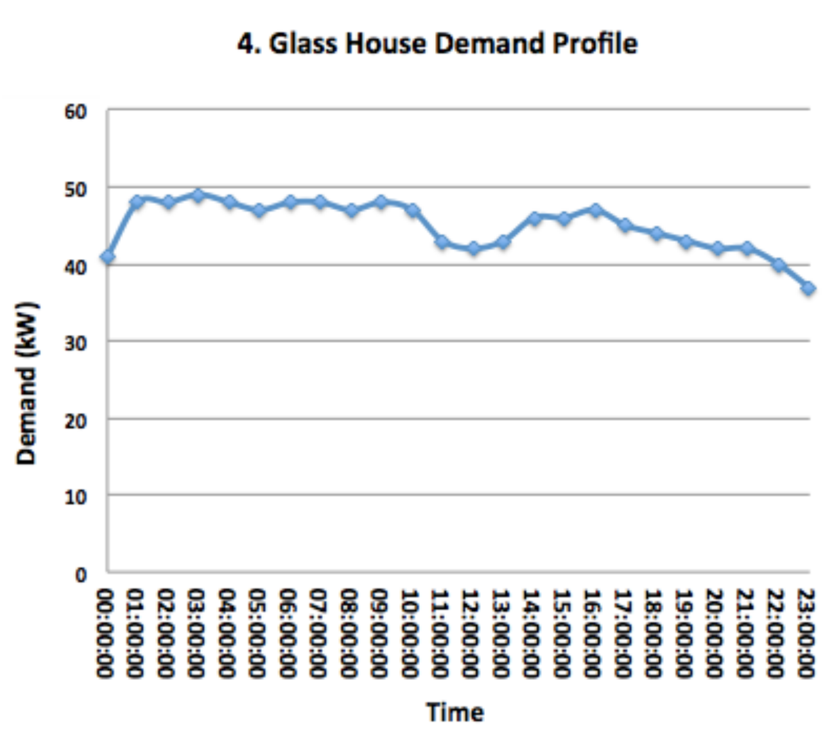
The first case study looks at a biomass boiler system for a typical green house. The demand profile was created for a hypothetical glasshouse using the sizing tool. The Biomass Boiler Sizing Tool requires building dimensions including glazing and wall areas to produce a demand profile. The characteristics of the glasshouse designed for the purpose of this case study were as follows:

Table 5.1.1: Glass House Characteristics

Glasshouse	Characteristic
Average Height	4 m
Floor Area	250 m^2
Total Glazing Area	370 m^2
Total Wall Area	70 m^2
Outdoor Design Temperature	-3°C
Internal Temperature	15°C
Site Location	Glasgow
Type of Glass House	Victorian
Solar Gains	5.3kW
Ventilation Rate	1.5 ach
Window Heat Loss	39.3kW
Wall Heat Loss	1.9kW

5.1.1. Demand Profile

Figure 5.1.1 below shows the demand profile for the green house, created for a design winter day. It can be observed that the profile shape is relatively flat and constant throughout the course of the day. This can have implication on the appropriate biomass boiler system configuration that should be selected.



Time	Demand (kW)
00:00:00	41
01:00:00	48
02:00:00	48
03:00:00	49
04:00:00	48
05:00:00	47
06:00:00	48
07:00:00	48
08:00:00	47
09:00:00	48
10:00:00	47
11:00:00	43
12:00:00	42
13:00:00	43
14:00:00	46
15:00:00	46
16:00:00	47
17:00:00	45
18:00:00	44
19:00:00	43
20:00:00	42
21:00:00	42
22:00:00	40
23:00:00	37

Figure 5.1.1: Diagram of Glass House Demand Profile

5.1.2. Training Tool Analysis

Once a demand profile had been created, each of the biomass boiler configurations can be analysed using the training tool. Each of the configurations has their own pros and cons and not all will be appropriate for this particular demand profile.

In this specific case study, the demand profile is relatively constant and flat throughout the course of the day. For this reason, there is little opportunity to use any heat stored overnight. Therefore, only a small thermal store will be required. Consequently, the biomass boiler should be sized at a relatively high percentage of the peak-heating load. In this case it is questionable if a thermal store will be worthwhile and an alternative option may be required. However, by analysing the systems performance with the training tool its effectiveness can be better understood.

It is important to stress that the training tool cannot be used alone to size a biomass boiler system. The tool is only capable of analysing the performance of a biomass boiler system for one demand profile at a time. However, if used alongside annual load duration curves and the Biomass Boiler Sizing Tool the training tool can become a useful design aid. However, the training tool is more useful as an educational tool for illustrating the operation of various biomass boiler configurations to a user during a 24-hour period. For this reason, the case study will concentrate mainly on the results given by the training tool for the 24-hour period of operation.

In this example, the peak-heating load is 49kW while the minimum-heating load is 37kW. However, the demand is above 45kW for approximately 54% of the day. This suggests that a boiler sized around 45kW would be able to provide a charge to a thermal store for almost half the day.

Despite the relatively flat demand profile associated with this glasshouse, the results from the training tool illustrate how a thermal store is advantageous in this particular scenario over the other configurations. This does not include the systems with auxiliary boilers since these systems are designed to provide 100% of the load, since the auxiliary boilers are rated at the difference between the biomass boiler rating and the peak demand.

Training Tool Results

The results shown in the Table 5.1.2.1 are a summary of the performance of each of the biomass boiler configurations. This includes the key characteristics of each system, including the boiler type and rating. The last column shows the percentage of the day that the biomass boiler system was capable of fully satisfying the demand from the load alone. This includes the periods in which the boiler cannot provide hot water due to its turndown ratio. Since there is no considerable difference in the performance of a two-port and four-port thermal store out to the load it has been assumed that the performance of each will be identical to the third row of results in Table 5.1.2.1.

Table 5.1.2.1: Training Tool System Results

Configuration Type	Boiler Characteristics	Boiler Rating	TS/BV Volume	Percentage of Energy Entirely From Biomass
1. No add-ons	• Moving Grate • Pellets • Thick Boiler Lining	48kW (98%)	NA	86.65%
2. Buffer Vessel	• Moving Grate • Pellets • Thick Boiler Lining	48kW (98%)	400 litres	92.39%
3. Thermal Store (includes BV)	• Moving Grate • Pellets • Thick Boiler Lining	45kW (92%)	750 litres	100% (Day 2)

Thermal Store Behaviour

Figure 5.1.2 below illustrates how the thermal store charges and discharges during the course of the second day of modelling. It shows how a thermal store with a volume of 750 litres is almost a perfect fit for this particular demand profile during the design winter day. The graph was generated from the results returned by the training tool.

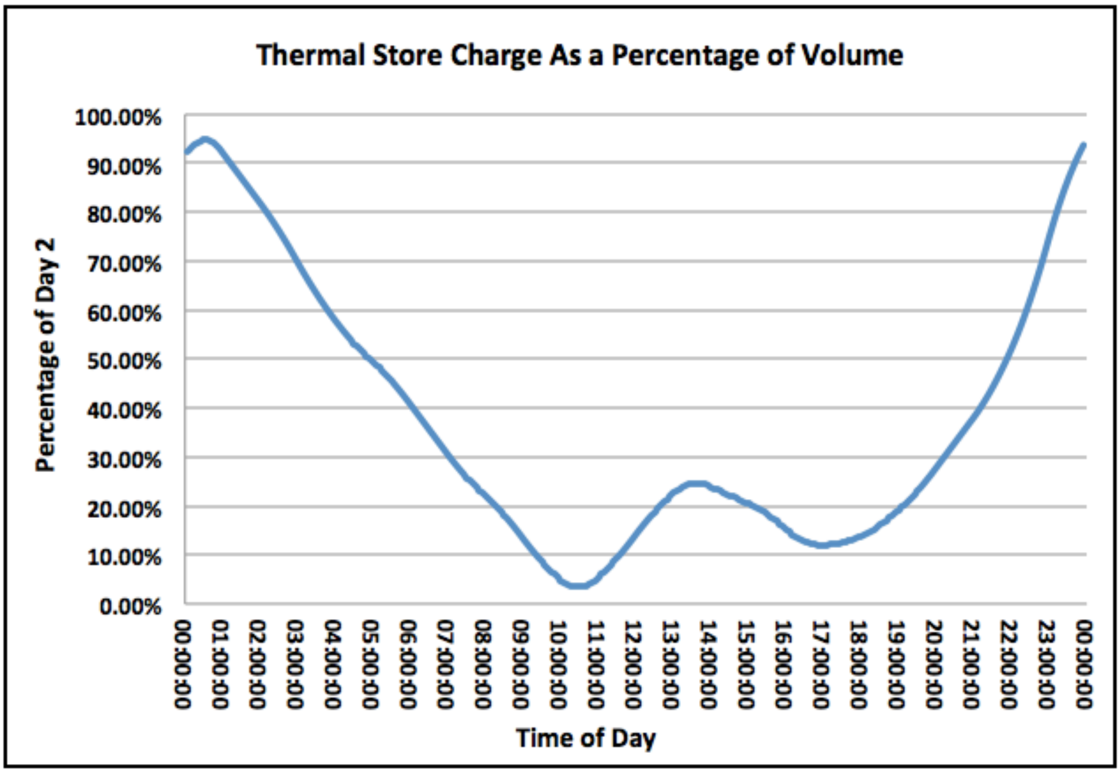


Figure 5.1.2.1: Thermal Store Charge As A Percentage of Volume

The thermal store starts the beginning of the second day with almost 95% charge of hot water. It then steadily decreases to just above 3% by 10am. The charge then reflects the shape of the demand profile by increasing briefly before discharging again to 11%. For the remainder of the day the rating of the boiler is above the demand from the load and the store charges back up to 95%. This shows that this particular system operates almost perfectly during the design winter day.

While the performance of the biomass boiler system during the second day is favourable, the training tool also indicates its poor performance during the first day since the thermal store is charged from cold at the start of the day. Table 5.1.2.1 below shows how the load is not satisfied at the start of the day while the boiler warms. It can also be observed how the temperature of the water provided to the heating system starts to fall below the required 50°C as the demand increases above the 45kW rating of the boiler.

Table 5.1.2.2: Table of Case Study System Results

TS charge (litres)	TS charge (%)	Boiler Tf (°C)	System Ts (°C)	System Tr (°C)	TS Flow (°C)	Boiler Tr (°C)	Boiler Work (kW)	Boiler Status	Load Satisfied?
0.00	0.00%	10.0	NA	NA	NA	10.0	45	WARM-UP	NO
0.00	0.00%	18.9	NA	NA	NA	18.9	45	WARM-UP	NO
0.00	0.00%	27.9	NA	NA	NA	27.9	45	WARM-UP	NO
0.00	0.00%	36.8	NA	NA	NA	36.8	45	WARM-UP	NO
0.00	0.00%	45.7	NA	NA	NA	45.7	45	WARM-UP	NO
0.00	0.00%	54.6	NA	NA	NA	54.6	45	WARM-UP	NO
0.00	0.00%	63.6	NA	NA	NA	63.6	45	WARM-UP	NO
0.00	0.00%	72.5	NA	NA	NA	72.5	45	WARM-UP	NO
0.00	0.00%	81.4	NA	NA	NA	81.4	45	WARM-UP	NO
0.00	0.00%	85.0	49.46	29.46	84	70.0	45	ON	NO
0.00	0.00%	85.0	49.22	29.22	83	70.0	45	ON	NO
0.00	0.00%	85.0	48.98	28.98	82	70.0	45	ON	NO
0.00	0.00%	85.0	48.75	28.75	82	70.0	45	ON	NO
0.00	0.00%	85.0	48.75	28.75	82	70.0	45	ON	NO
0.00	0.00%	85.0	48.75	28.75	82	70.0	45	ON	NO

Contrastingly, the table of results for the second day of modelling indicates the effectiveness of the thermal store during normal operations. Table 5.1.2.2 is a selection of the results for the start of the second day. Since the boiler has been operating over night to charge the thermal store it is already up the operating temperature (85°C) and the load can be satisfied from the very start of the day. When the demand increases above the rating of the boiler the thermal store starts to deplete to meet the demand. This can be seen as the thermal store charge percentage starts to fall from 94.72% to 89.53% in table 5.1.2.2.

Table 5.1.2.3: Table of Case Study System Results 2

TS charge (litres)	TS charge (%)	Boiler Tf (°C)	System Ts (°C)	System Tr (°C)	T From TS (°C)	Boiler Tr (°C)	Boiler Work (kW)	Boiler Status	Load Satisfied?
415.58	91.39%	85.0	50	30	85	70.0	45	ON	YES
420.02	92.36%	85.0	50	30	85	70.0	45	ON	YES
423.70	93.17%	85.0	50	30	85	70.0	45	ON	YES
426.62	93.81%	85.0	50	30	85	70.0	45	ON	YES
428.79	94.29%	85.0	50	30	85	70.0	45	ON	YES
430.19	94.60%	85.0	50	30	85	70.0	45	ON	YES
430.84	94.74%	85.0	50	30	85	70.0	45	ON	YES
430.74	94.72%	85.0	50	30	85	70.0	45	ON	YES
429.87	94.53%	85.0	50	30	85	70.0	45	ON	YES
428.25	94.17%	85.0	50	30	85	70.0	45	ON	YES
425.87	93.65%	85.0	50	30	85	70.0	45	ON	YES
422.73	92.96%	85.0	50	30	85	70.0	45	ON	YES
418.83	92.10%	85.0	50	30	85	70.0	45	ON	YES
414.94	91.24%	85.0	50	30	85	70.0	45	ON	YES
411.04	90.39%	85.0	50	30	85	70.0	45	ON	YES
407.14	89.53%	85.0	50	30	85	70.0	45	ON	YES

Further Analysis: Load Duration Curves

The annual load duration curve seen below has been generated to demonstrate the approximate performance of a boiler system rated at 92% (45kW) of the peak demand with a turndown ratio of 2.5:1. The area between the red and green lines in Figure 5.1.2.2 indicates the number of hours in the year that the boiler system is capable of satisfying the load. It can be observed that the boiler is sized appropriately for only 4300 hours of the year.

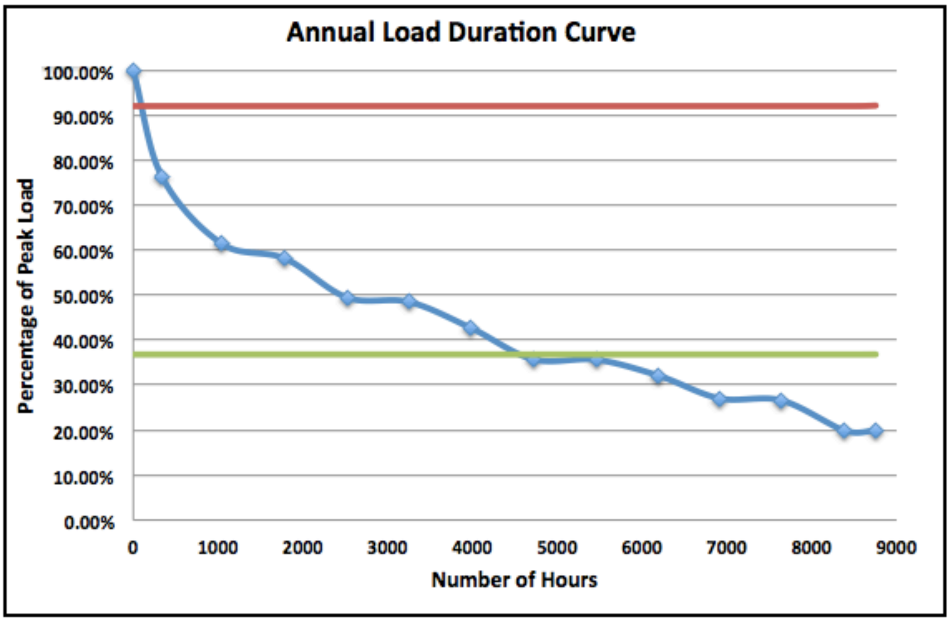


Figure 5.1.2.2: Case Study 1: Annual Load Duration Curve 1

Contrastingly, the boiler in the annual load duration curve seen below has a rating of 70% of the peak-heating load. In this example, shown in Figure 5.1.2.3 the boiler can match the demand from the load for an increased 6000 hours of the year, a large improvement on the previous boiler rating.

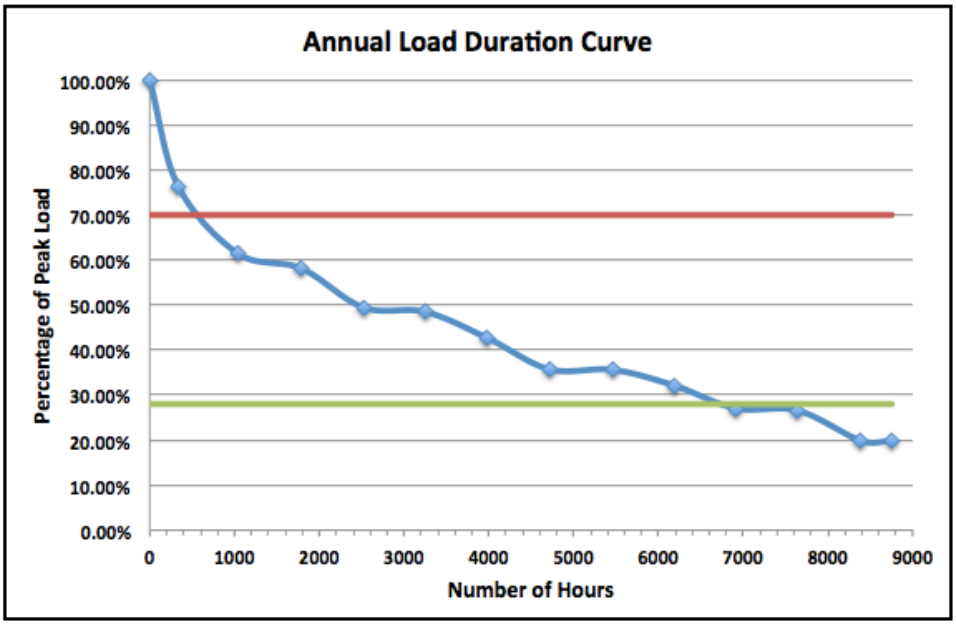


Figure 5.1.2.3: Case Study 1: Annual Load Duration Curve 2

While a boiler rated at 70% of the peak load may perform poorly during the design winter day, the annual load duration curve shows how it is appropriate for a large percentage of the year compared to a boiler rated at 92%.

However, the load duration curve does not take into account the volume of hot water that a thermal store can hold. When the load is below the turndown ratio of the biomass boiler a thermal store can act to feed the load with the hot water it requires. For this reason another demand profile has been created for a day with an outside temperature of 10°C instead of -3°C used for the design winter day. This demand profile is shown below in Figure 5.1.2.4.

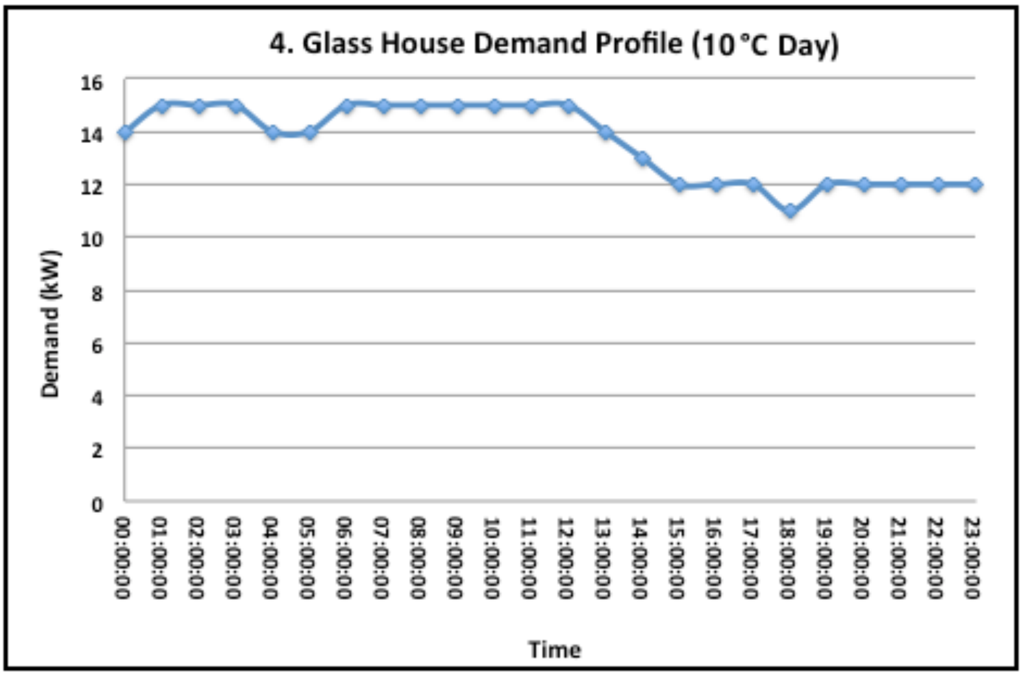


Figure 5.1.2.4: Summer Glasshouse Demand Profile

A boiler rated at 70% of the winter peak load has a minimum output of 13.7kW. The demand is above this minimum boiler output for approximately 58% of the day. This provides an opportunity for a thermal store to fill in the first half of the day and deplete during the remainder of the day when the demand is below the boiler turndown ratio.

Contrastingly, if the boiler is rated at 92% of the winter peak-demand, as in table 5.1.2, then the minimum output of the boiler is 18kW and the thermal store has no opportunity to fill and the load will be neglected for the entire day.

If a thermal store were not used then a boiler rated at 70% would not be able to satisfy the load during the later part of the day. For this reason it can be recommended that a thermal store of 750 litres is used alongside a biomass boiler of 35kW (70%) for this glasshouse. However, an auxiliary boiler would be a valuable addition to match the peak-heating load during the colder days of the year.

In this case study, the thermal store does not allow the biomass boiler to be sized at a much lower percentage of the peak demand due to the flatness of the demand profile. However, the next case study provides much more of an opportunity for hot water to be stored outwith the periods of peak demand. The required size of the thermal store is so small that it is only marginally larger (300 litres) than the buffer vessels volume. However, by using the tool to intelligently size the thermal store, a small increase in the volume of the thermal store can not only reduce the rating of the boiler but also significantly increase the performance of the system as a whole. This is also illustrated further in the next case study.

5.2. Case Study 2: Domestic Housing Estate

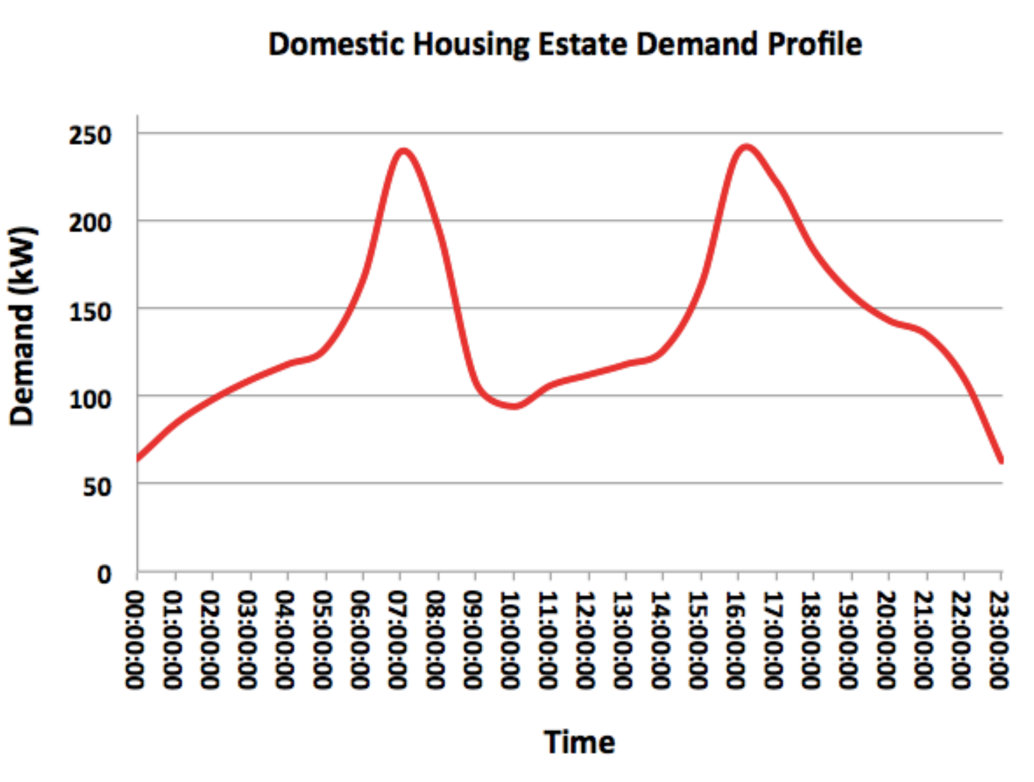
The second case study contains a collection of demand profiles combined into one to simulate a domestic housing estate. The housing estate is heated using a district heating network and a biomass boiler. The heating network includes several types and building and the following characteristics.

Table 5.2.1: Domestic Housing Estate Characteristics

Domestic Housing Estate	Characteristics
Location	Glasgow
Outdoor Design Temperature	-3°C
Average Heat Demand (Design Winter Day)	137kW
Energy Demand (Design Winter Day)	3283kWh
No. Of Detached Housing	10
No. Of Semi-detached Bungalows	10
No. Of Mid-Floor Flats	10
No. Of Top-Floor Flat	10

5.2.1. Demand Profile

Figure 5.2.1 seen below is a demand profile, which was created for a domestic housing estate during a design winter day. The values were ascertained from the Biomass Boiler Sizing Tool.



Time	Demand (kW)
00:00:00	64
01:00:00	84
02:00:00	98
03:00:00	109
04:00:00	118
05:00:00	127
06:00:00	166
07:00:00	239
08:00:00	196
09:00:00	108
10:00:00	94
11:00:00	106
12:00:00	112
13:00:00	118
14:00:00	126
15:00:00	163
16:00:00	239
17:00:00	222
18:00:00	183
19:00:00	158
20:00:00	143
21:00:00	135
22:00:00	110
23:00:00	63

Figure 5.2.1: Diagram of Domestic Housing Estate Demand Profile

Unlike the previous case study, this demand profile has two clear peaks where the demand for heating increases dramatically. Outwith these periods the demand ranges from almost 20% to 50% of the peak-heating load, while a heating demand is always present throughout the course of the design winter day.

5.2.2. Training Tool Analysis

The demand profile was uploaded into the training tool to analyse the performance of each of the configurations examined in this report. The training tool provides feed back for each configuration once the required data has been provided.

Similar to the previous case study, the shape of this demand profile suggests that a thermal store may be a useful addition to the chosen biomass boiler system. The profile has two clear peaks during the course of the day with a much lower heating demand outwith these periods.

The results shown in Table 5.2.2.1 are a summary of the performance of each of the biomass boiler configurations. This includes the key characteristics of each system, including the boiler type and rating. The last column shows the percentage of the day that the biomass boiler system was capable of satisfying the demand from the load alone. This includes the periods in which the boiler cannot provide hot water due to its turndown ratio.

Table 5.2.2.1: Table of Case Study 2 Main Results

Configuration Type	Boiler Characteristics	Boiler Rating	TS/BV Volume	Percentage of Energy Entirely From Biomass
1. No add-ons	• Moving Grate • Pellets • Thick Boiler Lining	200kW (83%)	NA	75.43%
2. Buffer Vessel	• Moving Grate • Pellets • Thick Boiler Lining	200kW (83%)	1665 litres	84.08%
3. Thermal Store (includes BV)	• Stoker Burner • Pellets • Thin Boiler Lining	140kW (58%)	4410 litres	80.28% (Day 1) 100% (Day 2)

From Table 5.2.2.1 it is clear that a boiler system, which includes a thermal store, performs much better than the other configurations. The thermal store has allowed the boiler to be rated at 58% of the peak demand and still satisfy the load 100% of the time during the second day of modelling.

Boiler Heat-Up Phase - Figure 5.2.2.1 is a graph to show how the water temperature increases around the back-end loop during the heat-up phase. This period is present when the load is first introduced for the first two configurations and at the very start of 'DAY 1' in the configuration which includes a thermal store.

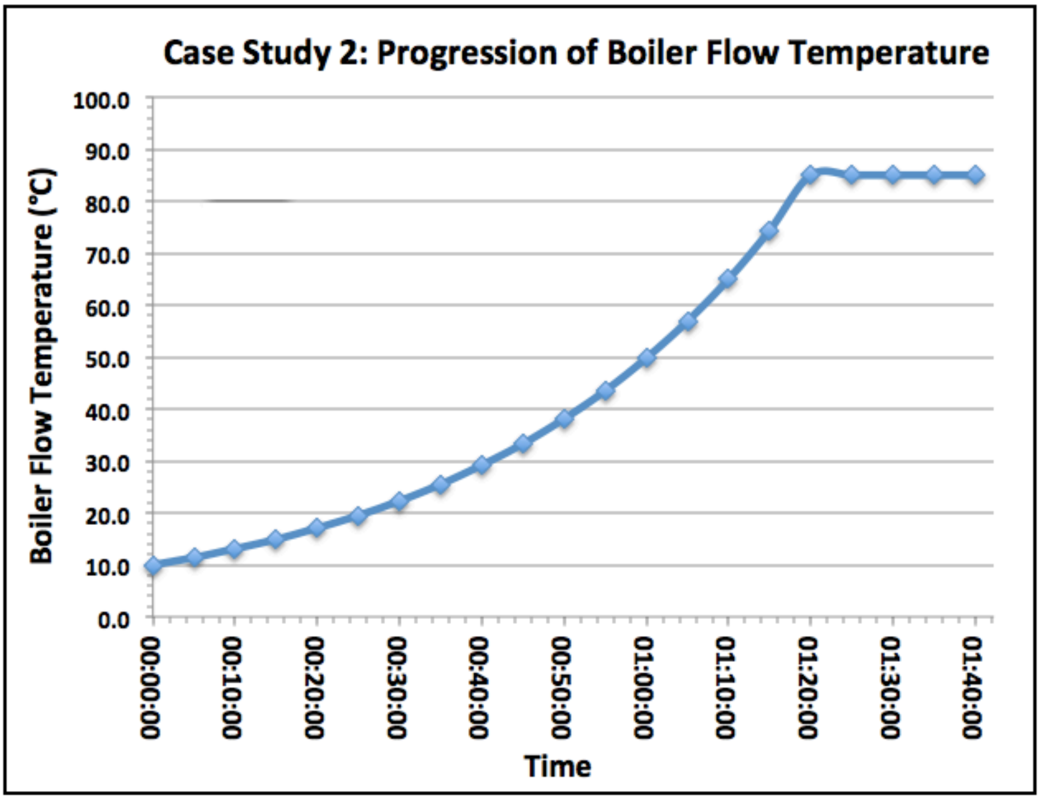


Figure 5.2.2.1: Case study 2: Boiler Heat-Up Phase

The results from the training tool show how the warm up period is 01:20:00 long. After this period the flow from the boiler remains at a constant temperature as it begins to feed the load. This is also illustrated in the table of results given by the training tool as in table 5.2.2.2 seen below. The water temperature increases exponential over the 01:20:00 period. Once the boiler set-point temperature has been reached the load is provided with hot water and the thermal store begins to charge (provided the demand is below the rating of the boiler).

Table 5.2.2.2: Case Study 2: Boiler Heat-Up Period

Time of Day	TS charge (%)	Boiler Tf (°C)	System Ts (°C)	System Tr (°C)	Boiler Tr (°C)	Boiler Status	Load Satisfied?
00:00:00	0.00%	10.0	NA	NA	10.0	WARM-UP	NO
00:05:00	0.00%	11.4	NA	NA	11.4	WARM-UP	NO
00:10:00	0.00%	13.1	NA	NA	13.1	WARM-UP	NO
00:15:00	0.00%	14.9	NA	NA	14.9	WARM-UP	NO
00:20:00	0.00%	17.1	NA	NA	17.1	WARM-UP	NO
00:25:00	0.00%	19.5	NA	NA	19.5	WARM-UP	NO
00:30:00	0.00%	22.3	NA	NA	22.3	WARM-UP	NO
00:35:00	0.00%	25.5	NA	NA	25.5	WARM-UP	NO
00:40:00	0.00%	29.2	NA	NA	29.2	WARM-UP	NO
00:45:00	0.00%	33.3	NA	NA	33.3	WARM-UP	NO
00:50:00	0.00%	38.1	NA	NA	38.1	WARM-UP	NO
00:55:00	0.00%	43.5	NA	NA	43.5	WARM-UP	NO
01:00:00	0.00%	49.8	NA	NA	49.8	WARM-UP	NO
01:05:00	0.00%	56.9	NA	NA	56.9	WARM-UP	NO
01:10:00	0.00%	65.0	NA	NA	65.0	WARM-UP	NO
01:15:00	0.00%	74.4	NA	NA	74.4	WARM-UP	NO
01:20:00	0.00%	85.0	50	30	85.0	ON	YES
01:25:00	1.56%	85.0	50	30	70.0	ON	YES
01:30:00	3.08%	85.0	50	30	70.0	ON	YES

Thermal Store Operation - Figure 5.2.2.2 illustrates how the thermal store charges and discharges under the housing estates demand profile. It can be observed how the thermal store charge reflects the shape of the demand profile for the housing estate.

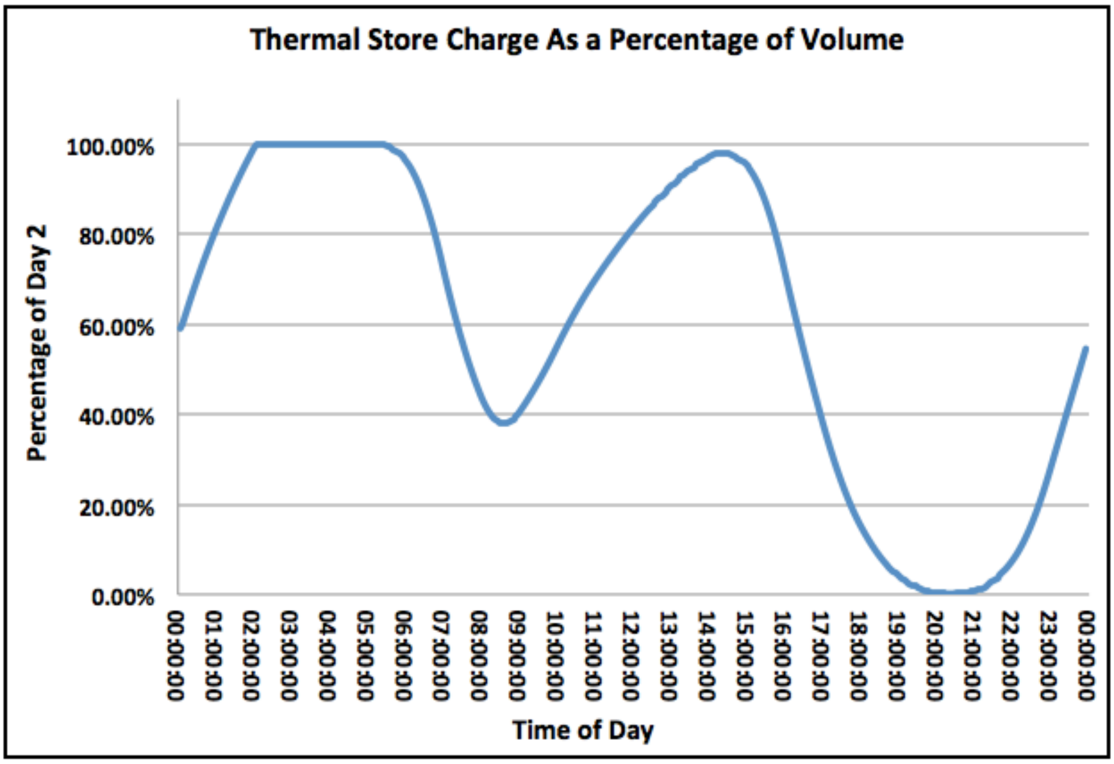


Figure 5.2.2.2: Thermal Store Charge As A Percentage Of Volume

The thermal store begins 'DAY 2' with a charge of approximately 59%. During the start of the day, this rapidly increases while the demand from the load is low, until it reaches its capacity at just after 2am. From this point the biomass boiler operates alone to feed the load since the demand is below the rating of the boiler and the thermal store charge remains at 100%.

Once the load increases above the rating of the boiler during the first peak (visible in the demand profile), the thermal store starts to deplete and the percentage falls. Once the demand from the load again falls below the rating of the boiler, the store begins to charge again to approximately 95%, in preparation for the second peak in the demand at 3pm.

Boiler and Thermal Store Sizing

The tool allows the boilers rating and the thermal stores volume to be altered independently to gauge the best sizes for the individual demand profile. Using the system feedback provided by the tool, the thermal store can be sized precisely to store the exact quantity of hot water needed throughout the design winter day while keeping its volume to a minimum. If there are space limitations for the thermal store the volume that is available can be chosen and the boilers rating adjusted to make up for the limitations in space.

In this case, the most suitable volume for the thermal store was found to be 4410 litres of which 224 litres acted as a buffer vessel. In can be observed in figure 5.2.2.2 that the percentage fluctuates from 100% to just above 0.1% suggesting that the thermal store is correctly sized for the design winter day. The graph also demonstrates how active the thermal store is throughout the course of the day. The store charges and discharges twice a day, which suggests that heat loss will be a minor component in the performance of the thermal store, an assumption made in the training tool.

Figure 5.2.2.3 shows how the performance of the biomass boiler system, which includes a thermal store increases as the volume of the thermal store is increased. The progression in performance is relatively linear with a sharp increase in performance as the volume approaches 4400 litres.

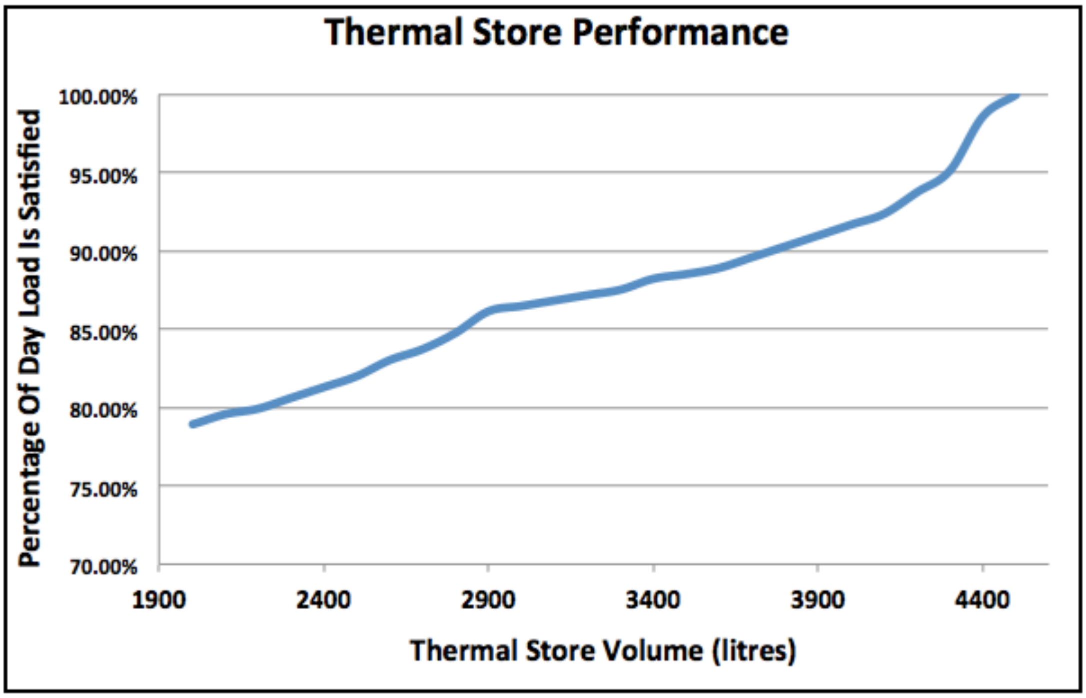


Figure 5.2.2.3: Case Study 2 Thermal Store Performance

Another valuable advantage that the thermal store provides over the other configurations is an improved minimum output from the biomass boiler. The configuration that includes only a buffer vessel has a turndown ratio of 4:1 and a minimum boiler output of 50kW. While, this is above the minimum demand for the design winter day, it may not be suitable during the summer months.

However, since the thermal store allows the biomass boiler to be rated at a much lower percentage of the peak-heating load the boilers minimum output is improved to 40kW and importantly the thermal store provides a supply of hot water when the demand is below 40kW.

To investigate this further, another demand profile was created for a design winter day in which the outdoor design temperature was chosen to be 10°C. The shape of the demand profile changed to account for the large change in the outside temperature. Figure 5.2.2.4 shows the design summer day demand profile.

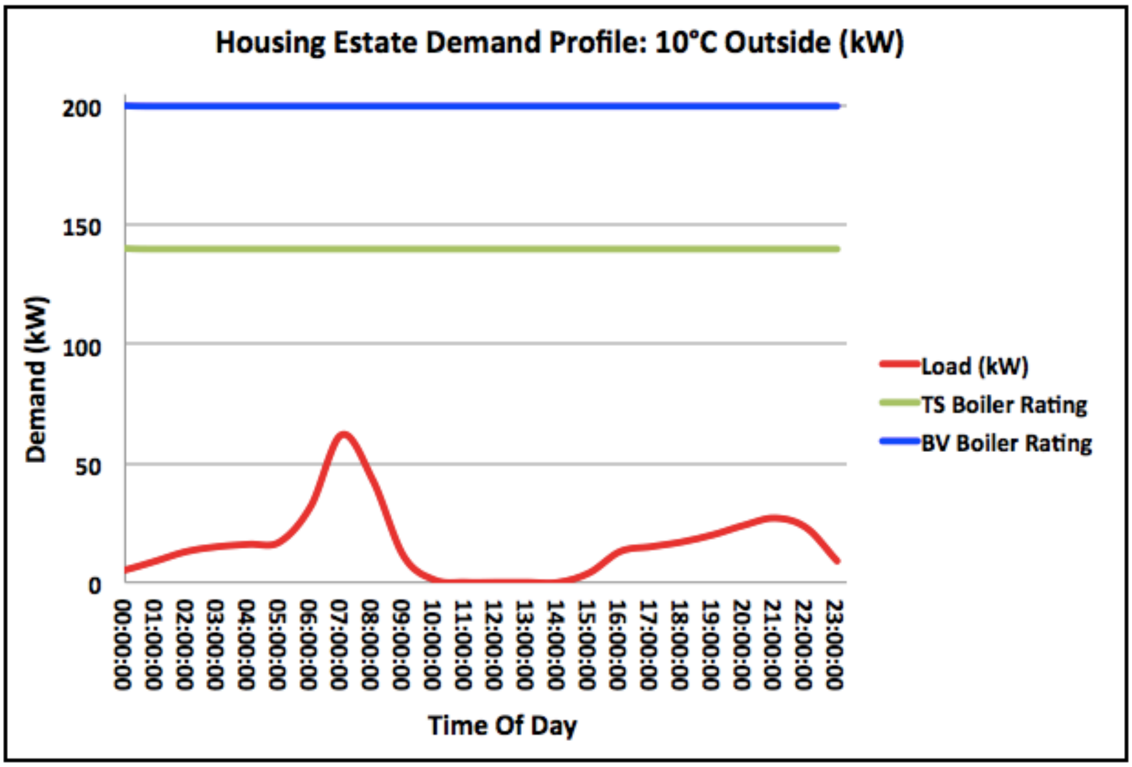


Figure 5.2.2.4: Case Study 2 Summer Demand Profile

The results seen below show the performance of the different configurations using this new demand profile but with the same boiler ratings as before.

1. **No add-ons**: 200kW boiler (83% of winter peak) satisfies the load for 4.76% of the day.
2. **Buffer Vessel**: 200kW boiler (83% of winter peak) satisfies the load for 4.76% of the day.
3. **Thermal Store**: 140kW boiler (58% of winter peak) satisfies the load for 100% of the day.

At the start of "DAY 1' the biomass boiler charges the thermal store until it has reached it capacity. This provides a large volume of hot water when the demand is below the turndown ratio of the boiler (40kW). For this reason, this biomass boiler systems design is capable of satisfying the load fully during the design summer day as well as the design winter day, while the other configurations provide very little. Consequently, a biomass boiler system with the following characteristics can be suggested for this housing estate.

Table 5.2.2.3: Case Study 2 System Recommendations

Boiler Rating	140kW (58% of peak demand)
Thermal Store Volume	4410 litres (includes BV volume)
Buffer Vessel Volume	224 litres
Boiler Type	Stoker Burner
Feed Mechanism	Auger
Refractory Ling Thickness	'Low'
Boiler Turndown Ratio	3.5:1

6. Discussion and Future Developments

This section of the report will discuss the advantages and disadvantages of the training tool and highlight areas that can be improved by future developments and research. At the very least, the training tool has been demonstrated to be a useful representation of the operation of each of the configurations that have been modelled. The training tool models the key phases associated with selected biomass boiler systems and the performance and operation of several system components and hydraulic configurations. The introduction of this report discussed the problems associated with incorrectly sized biomass boiler systems. If used as an educational model, the training tool could avoid these issues by improving the users understanding of these biomass boiler systems. This could result in the following benefits:

1) Correctly sized biomass boilers, buffer vessels and thermal stores for new installations.
2) Improved design of newly installed biomass boiler systems
3) Increases in the efficiency of biomass heating systems by avoiding unnecessary boiler cool-down and heat-up periods.
4) Reduction in quantity of fuel used by efficient system design saving money and reducing harmful carbon emissions.
5) Increases in the percentage of the year that biomass boilers can provide heating, avoiding the use of auxiliary fossil fuelled heating systems and the associated emissions.

The dynamic diagrams which were included into each of the configurations modelled provided a methods of visualising the operation of the different components in a faster than real time simulation. While the simulations were valuable, they could be developed further to improve their performance. Because of the number of calculation being made by the macro during the simulations and the limitations of Excel the diagrams often ran slow and skipped steps. If the training tool was developed using the same equations within a java based program instead of an Excel spreadsheet the diagrams could run much more smoothly, improving the user experience.

As of now, three key biomass boiler systems have been modelled within a training tool. However, there are many other biomass boiler configurations that are used with slight differences. These slight differences may have a large influence on how each system operates. For this reason it would be useful if the training tool was developed in the future to include as many configurations as possible so that it could be used to model a wider variety of biomass boiler systems.

Next, with any modelling of this kind there is a degree of inaccuracy in the results due to the assumptions made to analyse the different configurations. There have been several assumptions made for each of the configurations investigated within this report. Each of these assumptions will have an impact on the accuracy of the results given for each of the demand profiles investigated.

For example, it was assumed in the training tool that the thermal stores that are modelled include perfect stratification using sparge pipes. However, in reality this is unlikely to be the case as mixing between the layers of hot and cold water is unavoidable to a certain extent. In fact, given enough time the hotter layer of water will transfer heat down the thermal store via conduction even if the mixing between the layers is completely avoided. For these reasons it would be valuable if the training tool was developed to include an element of mixing within the thermal stores.

Similarly, it is also important to consider the heat loss associated with the storage of hot water inside a buffer vessel or thermal store. In the training tool it has been assumed that the temperature of the water stored within these vessels remains constant as long as it remains inside the vessel. For short periods of time this assumption may be reasonable, but for longer storage periods heat loss from the thermal store may become an issue. However, the case studies included in this report have shown how the thermal stores are very active throughout the course of the day, sometimes charges and discharging several times, meaning the hot loss can be considered negligible for the demand profiles considered.

One of the more challenging areas of the project to model was the heat-up and cool-down periods associated with biomass boilers. Approximations of these periods were including into the training tool after several assumptions were made.

The exact processes that biomass boilers undertake during these periods are heavily reliant on the manufacturers design. The heat-up and cool-down periods are subject to the internal design of the individual boiler. This includes the boiler dimensions, the thermal properties of the boiler components, and the thickness and shape of the refractory lining within the biomass boiler. The exact thermal mass will vary from one boiler design to another, which effects the quantity of heat that must be extracted from the boiler when shut down and the length of time for the boiler to heat up. In fact, the internal temperature that the boiler must to be cooled to will vary from one boiler to the next depending on the manufacturers design. Typically, while the boiler is heating up before hot water is supplied to the load the flow will circulate round the back-end loop at a constant flow rate until the water is up to the designed flow temperature. However, numerous boilers will vary the flow rate around the back-end loop during the boiler heat-up period.

The training tool aims to estimate the progression of the boiler flow temperature around the back-end loop. Once a length of time has been calculated to heat up the total thermal mass of the boiler the temperature progression has been assumed to be linear over that time period. However, this is unlikely to be the case as the different elements of the boiler heat at different rates. The heat up of the thermal lining occurs from burning wood gas and radiated heat from the grate. Assuming a constant combustion rate the amount of heat absorbed by the lining is a function of the temperature difference between the flame and the thermal lining. As the lining heats up the temperature difference between the flame and the lining and, hence, the heat input decreases. So the process is non-linear and is usually regarded as exponential.

Similarly, when the load is removed from a biomass boiler some boilers initiate a cool-down period while others enter a slumber mode by feeding a small amount of fuel onto the combustion chamber. All in all, the exact operation of biomass boilers during start up and shut down is highly dependent on the specific boiler characteristics. However, the training tool has included a representation of both of these periods so that it can be demonstrated to the user of the tool.

It would be useful if these approximations were improved to mimic the behaviour of biomass boilers during these periods more accurately. Unfortunately, short of constructing thermal models of several different biomass boilers, it proved difficult to improve upon the approximations made to model the heat-up and cool-down periods during the scope of this project due to time constraints and limitations in the boiler data available.

Once these developments have been made it would be valuable if test data could be obtained from sites with the same boiler configurations as currently included in the training tool. This would allow the results provided by the tool to be compared and verified and allow engineers to use the tool with confidence when installing a biomass boiler system.

Finally, to allow the training tool to be as flexible as possible it would be useful to include as many additional heating options as possible, such as a variety of auxiliary heating equipment. This could include solar thermal panels to preheat the return temperature to the biomass boiler or multiple auxiliary boilers in various locations across the piping network.

7. Conclusion

The purpose of this study has been to develop a training tool that can be used to assist those interested in understanding the inner workings of biomass boiler systems. The tool has been developed within Microsoft Excel to model three common piping configurations used within biomass boiler systems. This includes calculating the flow rates and temperatures throughout each configuration for five-minute time step through an entire day of operation.

The case studies within this report have shown how a thermal store can be used to reduce the size of biomass boiler by providing a store of hot water in times of high demand. Contrastingly, the first case study has illustrated how the shape of a demand profile can have large implications on the effectiveness of additional components such as thermal stores. The results from the second case study have also shown how a thermal store can improve a biomass boiler systems performance when the heating demand is below the turndown ratio of the particular boiler, by providing a store of hot water than can be utilised. This is more applicable in summer months when the demand for heating is reduced.

The case studies have also illustrated the operation of each of the biomass boiler systems and shown how the training tool can improve a users understanding of the performance of different system components and hydraulic configurations.

Each configuration contains its own complexity, which is reflected within the equations used. With further development the tool could be used as an addition to the Biomass Boiler Sizing Tool developed by the Carbon Trust to assist engineers when designing and installing a biomass boiler system. The report illustrates how the two tools can be used in partnership with each other to develop and analyse a biomass boiler system for a given demand profile. If the accuracy of the results given by the tool for each configuration can be verified with recorded test data then this objective is an achievable goal. However, before the training tool can reach this objective much development must take place in the areas previously discussed in section 6 of this report.

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9. Appendix

9.1. Demand Profile 3: Swimming Pool

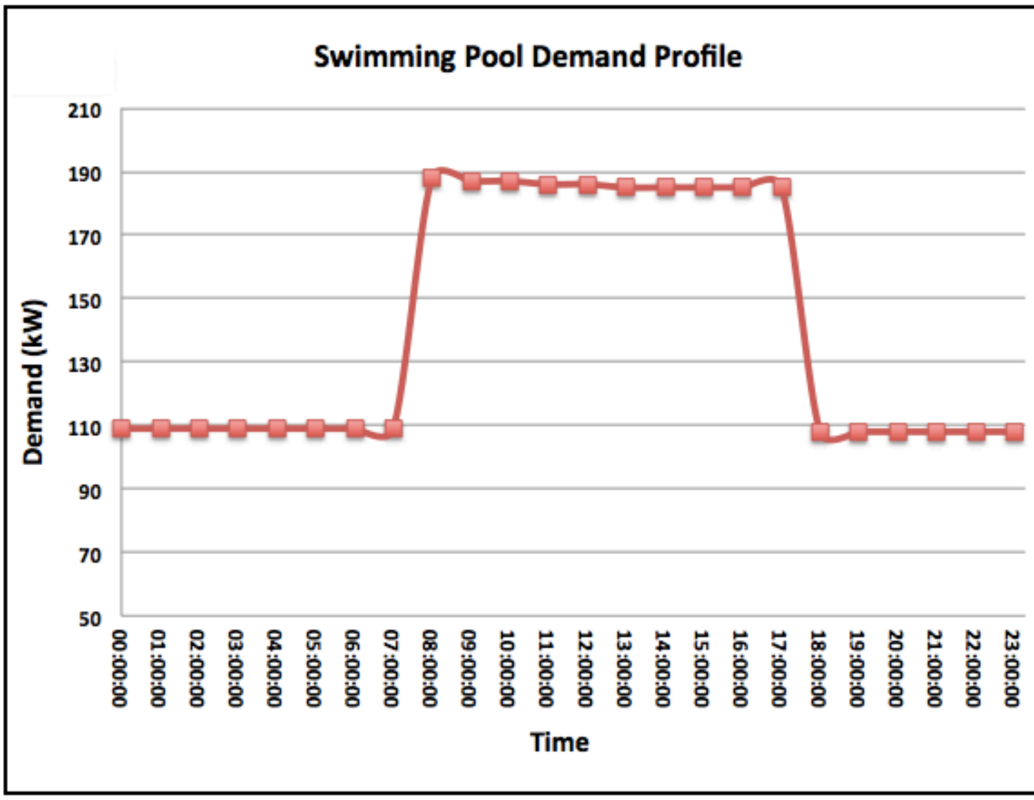
The third demand profile was created for a standard swimming pool. The swimming pool modelled had the following characteristics.

Table 5.2: Swimming Pool Characteristics

Swimming Pool	Characteristics
Type of Pool	Leisure pool (few water features)
Heating Days A Week	7
Operating Hours Per Day	Short
Pool Water Temperature	29°C
Outdoor Design Temperature	-3°C
Length	25m
Width	10m
Pool Hall Floor Area	$400m^2$
Pool Hall Height	5m
Total Glazing Area	$12m^2$
Total Wall Area	$320m^2$
Heat Recovery System	Heat Pump Dehumidifier
Average Number of Bathers	15

Demand Profile

Figure 9.1.2 below shows the demand profile for the swimming pool and the hourly heating data.



Time	Demand (kW)
00:00:00	109
01:00:00	109
02:00:00	109
03:00:00	109
04:00:00	109
05:00:00	109
06:00:00	109
07:00:00	109
08:00:00	188
09:00:00	187
10:00:00	187
11:00:00	186
12:00:00	186
13:00:00	185
14:00:00	185
15:00:00	185
16:00:00	185
17:00:00	185
18:00:00	108
19:00:00	108
20:00:00	108
21:00:00	108
22:00:00	108
23:00:00	108

Figure 9.1.2: Diagram of Swimming Pool Demand Profile

9.2. Demand Profile 4: Non-Domestic Building

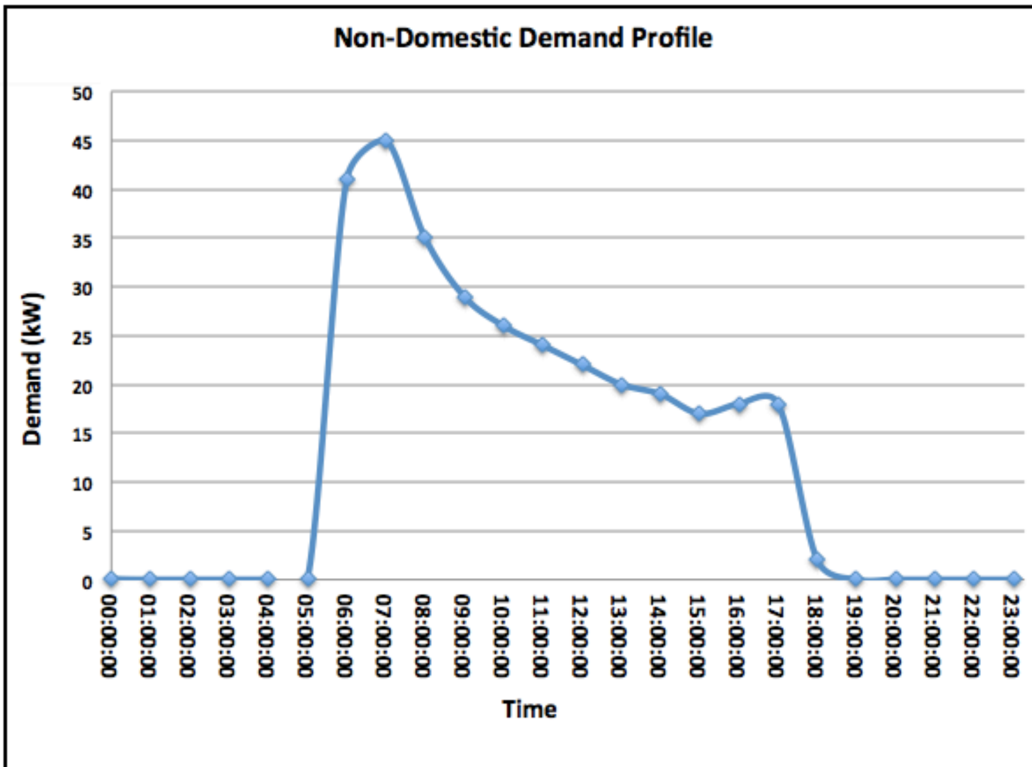
The fourth demand profile was creasted for an office block in Glasgow with the following characteristics. The sizing tool used the following data to create the demand profiled used for the purpose of this case study.

Table 5.3: Non-Domestic Building Characteristics

Non-Domestic Building	Characteristic
Site Location	Glasgow
Building Thermal Mass	Light
Internal Temperature	20°C
Outdoor Design Temperature	-3°C
Total Floor Area	$600m^2$
Total Wall Area	$7200m^2$
Level of Insulation	Medium
Total Glazing Area	$600m^2$
Level of Occupancy	Short
Average Heat Demand	13kW
Total Solar Gains	340W
Average Occupancy	50 people
Building Type	Offices

Demand Profile

The demand profile for the office building investigated is shown below in Figure 9.2.2, along with a table of the hourly heating demand.



Time	Demand (kW)
00:00:00	0
01:00:00	0
02:00:00	0
03:00:00	0
04:00:00	0
05:00:00	0
06:00:00	41
07:00:00	45
08:00:00	35
09:00:00	29
10:00:00	26
11:00:00	24
12:00:00	22
13:00:00	20
14:00:00	19
15:00:00	17
16:00:00	18
17:00:00	18
18:00:00	2
19:00:00	0
20:00:00	0
21:00:00	0
22:00:00	0
23:00:00	0

Figure 9.2.2: Diagram of Non-Domestic Building Demand Profile

9.3 Dynamic Diagrams Example Coding

Below is an example of the coding used to simulate the operation of the individual biomass boiler configurations. This example coding allows the operation of a thermal store to be simulated within the Excel training tool. In other words, the user can visualise the hot water interface moving up and down the length of the thermal store as it is charged or depleted.

```
Sub Macro1()
' Macro1 Macro
Dim i As Integer
For i = 61 To 120
i = i + 1
Application.Wait Now + TimeSerial(0, 0, 0.6)
    Cells(i, 17).Select
    Selection.Copy
    Range("P3").Select
    Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False
Next i
End Sub
```

In the example above, the results to be displayed in the diagram begin in row number 61 and end in row 120. In other words, the charge of the thermal store for each time step is listed from cells (61,17) down to cell (120,17). Each value is in turn copied and pasted into a reference cell. This cell is used to determine the condition of the thermal store in the diagrams for each time step.

The results for each time interval are copied and the values only pasted into cell 'P3'. The diagram is linked to cell 'P3'. The dynamic diagram will alter to take account for the changing value within cell 'P3'. Conditional formatting was used within each cell of the thermal store to achieve the desired simulation. The details of this process are shown in section 4.3 of this report.

The coding *'Application.Wait Now + TimeSerial(0, 0, 0.6)'* pauses the loop after each change in 'i' for 0.6 seconds to ensure that each change to the value within cell 'P3' is visible to the user in the diagram.